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CLIMATIC CHANGE IN CANADA 3

C.R. Harington, Editor

No. 49 1983

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Syllogeus Series No. 49
(c) National Museums of Canada 1983
Printed in Canada
ISSN 0704-576X

Serie Syllogeus No. 49
(c) Musées nationaux du Canada 1983
Imprimé au Canada

COVER: NMNS CLIMATIC CHANGE PROJECT SYMBOL
DESIGNED BY ELEANOR KISH

CLIMATIC
CHANGE
IN CANADA 3

DEDICATION

This volume is dedicated to the memory of Richmond W. Longley (1907-1981), a pioneer in the study of climatic variability in Canada.

CLIMATIC CHANGE IN CANADA 3

National Museum of Natural Sciences
Project on Climatic Change in Canada
During the Past 20,000 Years

Edited by C.R. Harington

Syllogeus No. 49

National Museums of Canada
National Museum of Natural Sciences

Les Musées nationaux du Canada
Musée national des sciences naturelles

ACKNOWLEDGEMENTS

The editor is grateful to: Mr. C.G. Gruchy (Acting Director, National Museum of Natural Sciences) and Mr. Ridgeley Williams (Acting Assistant Director, Research and Operations, National Museum of Natural Sciences) for their support; his colleagues in the Paleobiology Division for their continuing interest in and encouragement of the project; the contributors of papers for their care and patience during the editing process; and Mrs. Dolcis La Page (Sussex Informatics Limited) for supervising final typing of the manuscripts. Above all, the editor wishes to thank Mrs. Gail Rice (Assistant to the Division Chief, Paleobiology Division) for help in all phases of this project including preparation of the final draft of this publication. Eleanor Kish and Charles Douglas kindly provided the NMNS Climatic Change Project symbol (cover) and the novel graphic design (inside cover). Mr. A. Stewart (National Museum of Natural Sciences Branch Librarian) and librarians at Environment Canada in Ottawa and the Canadian Climate Centre at Downsview kindly aided by tracing difficult references.

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INTRODUCTION

C.R. Harington[1]

This is the third publication in a series arising from the National Museum of Natural Sciences climatic change project. The first volume, *Climatic Change in Canada* (*Syllogeus* No. 26, 1980) was largely devoted to a review of methodology as applied to paleoclimatic data and a compilation of pertinent paleobotanical data having potential value for interpretation of climate in Canada during the past 20,000 years. The second volume, *Climatic Change in Canada 2* (*Syllogeus* No. 33, 1981) covered a broader field, provided more in the way of interpretation, and included papers by associates of the project - in addition to those of members whose work was funded through the project.

This volume continues the trend of *Climatic Change in Canada 2*, and is dedicated to the late Richmond W. Longley. I first encountered him, by voice only, as an energetic forecaster at Resolute, Northwest Territories while reporting (when atmospheric conditions and a temperamental radio transmitter allowed!) weather from an isolated International Geophysical Year base on northern Ellesmere Island. Several years later, while carrying out postgraduate work at the University of Alberta, I had the extreme good fortune to meet with him regularly for a tutorial on climates of the past. Often we concluded our sessions by discussing such subjects as the vagaries of prairie hail storms and cloud-seeding, but regardless of the particular topic, he displayed intense enthusiasm for his chosen field and an encyclopedic knowledge of it. At the close of this publication, John Powell, in a paper on Longley's contributions to the study of climatic variability in Canada using the meteorological record, demonstrates that Longley was a Canadian pioneer in this field.

Some highlights of the other papers in this volume are reviewed below in order to give a brief idea of their scope and show where they may complement or contrast with one another.

The publication opens with two timely and stimulating papers on future climate in Canada. F.K. Hare, the renowned climatologist and geographer, discusses potential climatic warming due to continuing injection of CO_2 into the atmosphere, and the effects this could have on our economy. For example, a century from now the climate of southern Manitoba may resemble that of southern Minnesota today, and arctic pack ice may have disintegrated - factors which would significantly influence our agricultural production and shipping in the Arctic. He emphasizes that the key word is may, and that if certain climatic modelling predictions come true they do not imply inevitable disaster, but rather that we should seriously consider the possible results and search for useful ways of adapting to possible changes. Finally, he notes that the CO_2 "problem" is a global one and argues that our participation in the World Climate Programme and similar efforts is not merely a duty, but a protection of our national interest.

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Fisher and Koerner state that analyses of ice cores from High Arctic ice caps can provide valuable paleoclimatic information. They point out that ideas concerning the nature of future climatic changes seem to vary according to scientific "fashions" of the time, and stress the need for better estimates so that adequate contingency plans can be developed for meeting the possible changes. Analyses of their past data indicate a continuation of the present cooling trend (likely involving a drop in annual temperature of 0.5 to 1.0°C) to at least 1990, and perhaps beyond. Such a prediction is of considerable interest to those concerned with shipping in the Canadian Arctic. Presently, the authors are somewhat skeptical of predictions based on anthropogenic (including CO_2) influences. They suggest, at least, that CO_2-related warming predictions should be incorporated with extrapolations of proxy temperature records, such as theirs, to estimate more realistically future climatic change in the Canadian Arctic.

Where predictions are made for such complex natural systems as that of the biosphere-ocean-atmosphere, our lack of detailed understanding of the mechanisms (e.g. the carbon cycle) can seriously affect the value of the results. Conceivably, "buffering" effects within the overall system that have not yet been allowed for, could greatly dampen CO_2-related warming. Time will tell!

What can be said about past atmospheric conditions from glaciological data? Bea Alt notes that by coupling data from Canadian High Arctic ice-core studies (such as those of Fisher and Koerner) with a series of synoptic analogs based on relatively simple synoptic classifications, certain assumptions can be made about climates in the region during the past 5,000 years. Thus, synoptic analogs derived from present extreme conditions for the Queen Elizabeth Islands are capable of reproducing the magnitude of observed climatic differences between the 1961-1977 study period and "critical" periods (e.g. Little Ice Age, Medieval Warm Period). However, there is no proof that the synoptic patterns discussed are the only ones capable of causing temperature changes deduced from ice-core oxygen isotope records. It is worth noting that the method Alt applies to this study could be applied to other parameters such as seasonal variations in sea ice, flora or fauna.

Continuing on the subject of ice, John Newell, after much patient sifting of data, shows that ice conditions in the Labrador Sea during the nineteenth century were significantly more severe than present normals for that area. And, for nearly half of the years, conditions were more severe than the present extremes. The severity of ice conditions during the decade 1810-1819 in the Labrador Sea supports Faurer's (1980) findings for Hudson Strait during that period (see also Catchpole and Ball 1981, Figures 8, 9). Newell is currently investigating the relationships between changing nineteenth century ice conditions in the Labrador Sea and changing climatic conditions.

The Prairie Provinces periodically experience long dry spells, which can have important socio-economic repercussions. As a contribution to the understanding of such conditions, Street and McNichol provide a systematic study of soil-moisture conditions in the region from 1925 to 1980. Their decadal analyses show a remarkable degree of variation in prairie soil moisture in both space and time during this period. For the decade 1971-1981, the authors detect a westward shift in soil-moisture minimum values from southeastern Saskatchewan to southern Alberta and southwestern Saskatchewan. What were the climatic causes of this shift? Obviously more work is required before arriving at a deeper understanding of soil-moisture and drought characteristics in the Prairie Provinces. It is important to take up this challenge, because our prairies are the "breadbasket" of the nation. Furthermore, the produce of the region - because of its importance in terms of world exports - can have significant geopolitical effects.

One of North America's great paleoclimatic treasures is the mass of documents (post journals, ships' logs and instrumental records) in the Hudson's Bay Company archives in Winnipeg. A great deal of credit must go to Alan Catchpole, Tim Ball, Cynthia Wilson and their co-workers who have been painstakingly extracting past climatic information from these documents for many years. In this volume, Cynthia Wilson analyzes Hudson's Bay Company temperature records for the east coast of Hudson/James Bay during the unusually cold period 1814-1821. Evidence suggests that these early temperature records from Whale River, Big

River and Eastmain, when properly calibrated, are comparable in value with modern series from the region. Like Newell's, her study reveals that the period dealt with was generally cooler than the present, and that the summers of 1816 and 1817 were colder than any on modern record. The next phase of the study is to provide a detailed climatology of this period, and a comparison with recent climate in this region.

Tim Ball is similarly optimistic about the quality and value of early instrumental temperature records from the west coast of Hudson Bay. After testing the accuracy of the records for York Factory and Churchill Factory, he lists their important features, showing how they compare with recent temperature means for Churchill. At York Factory, which has the longer series of instrumental records, there are two periods without temperature records from 1774 onward. Ironically, these gaps in 1814 and 1816 may be due to such bad weather that human survival was deemed to be more important than record keeping! Undoubtedly, these remarkable Hudson's Bay Company records will be prized more highly as they become better known.

The study of tree rings in ancient wood can also contribute to the paleoclimatic record. Dealing with the same part of the west coast of Hudson Bay as Ball; Parker, Bramhall and Johnson show that, although their living-tree chronology for the Churchill area goes back only to 1870, driftwood from raised beaches farther south at Owl River extends the tree-ring chronology back to 1656. Parker *et al.* demonstrate that crossdating between living-tree site chronologies up to 965 km apart is possible by matching the Churchill River (Manitoba) black spruce record with that of Cri Lake (Québec) white spruce (see Parker *et al.* 1981, p. 129) on the opposite coast of Hudson Bay. Where paleoclimatic interpretations are concerned, the authors conclude that maximum ring density correlates best with August temperature. The possibility that a regional dendroclimatological record may be extended back thousands of years by working back through progressively older driftwood logs on higher beaches farther inland is most intriguing.

Webb, Richard and Mott, using a large series of maps summarizing data from a network of 43 radiocarbon-dated pollen diagrams, outline the sequence of Holocene vegetational change in southern Québec. From 10,000 to 6,000 yr B.P., first aspen woodlands and then spruce, fir and birch forests replaced the treeless or open vegetation that occurred north of the Champlain Sea 10,000 years ago. These forests moved northward until 6,000 yr B.P. Forests rich in pines entered the region from the southwest at 9,000 yr B.P., became widespread by

8,000 yr B.P., and were largely replaced by mixed forests. Hemlock became widespread in the south by 5,000 yr B.P., declined in abundance about 4,700 yr B.P., and reemerged strongly after 3,000 yr B.P. In addition to noting the marked assymetry that characterizes the Holocene vegetational history of the region, the authors stress that the early Holocene may have been drier than the late Holocene, and the seasonal contrast in the early Holocene may have been greater than that of today. Work in deciphering climatic and other factors controlling the observed vegetational changes will be promoted when this piece of the puzzle is aligned with other similar pieces from adjacent areas.

In conclusion, I wish to mention that the fourth meeting of the National Museum of Natural Sciences climatic change project (and its first international meeting) entitled "Critical Periods in the Quaternary Climatic History of Northern North America" will be held in Ottawa on May 19 and 20, 1983. I hope that this meeting will give the participants, representing various disciplines, an opportunity to focus on, and discuss the nature of, such conspicuous past climatic events as the Hypsithermal, the Little Ice Age and "the year without a summer" (1816). Also, I am pleased to report that Anne Smithers, a contractor to the project, has completed the last annotations and index for the "Annotated Bibliography of Quaternary Climatic Change in Canada". With luck, it should be available in 1984.

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AVANT-PROPOS

C.R. Harington[1]

Cette publication est la troisième d'une série découlant du programme de changement climatique du Musée national des sciences naturelles. Le premier volume, intitulé *Climatic Change in Canada* (*Syllogeus* n° 26, 1980), est consacré en grande partie à l'étude de la méthodologie appliquée aux données paléoclimatologiques ainsi qu'à l'établissement des données paléobotaniques qui peuvent servir à l'interprétation du climat canadien des 20,000 dernières années. Le deuxième volume, intitulé *Climatic Change in Canada 2* (*Syllogeus* n° 33, 1981), couvre un champ plus vaste, est davantage axé sur l'interprétation et contient des études de spécialistes associés au programme en plus de celles des collaborateurs dont les travaux ont été financés grâce au programme.

Poursuivant la même orientation que *Climatic Change in Canada 2*, le présent volume est dédié à la mémoire de Richmond W. Longley. Mon premier contact avec lui eut lieu par le truchement de la radio lorsque, météorologue énergique à Resolute dans les Territoires du Nord-Ouest, il annonçait la météo (lorsque les conditions atmosphériques et un mauvais émetteur le permettaient!) dans une base isolée située dans le nord de l'île Ellesmere dans le cadre de l'Année géophysique internationale. Quelques années plus tard, lorsque je poursuivais des études supérieures à l'Université de l'Alberta, j'eus la chance extraordinaire de le rencontrer régulièrement pour des travaux portant sur les climats du passé. Nous terminions souvent nos séances en discutant de questions telles que les capricieux orages de grêle des prairies et l'ensemencement des nuages, mais quel que fût le sujet, il montrait un vif enthousiasme et une connaissance encyclopédique du domaine qu'il avait choisi. Cet ouvrage se termine par une étude de John Powell consacrée à l'apport de Longley à l'étude des variations climatiques au Canada à partir des données météorologiques, où l'auteur démontre que Longley fit oeuvre de pionnier dans ce domaine.

Certains des faits saillants des autres études publiées dans ce volume sont examinés dans le compte rendu suivant, qui donne une idée sommaire de la portée des différents travaux et montre en quoi ils peuvent se compléter ou s'opposer l'un à l'autre.

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L'ouvrage débute par deux études opportunes et stimulantes portant sur l'avenir du climat canadien. Le climatologue et géographe renommé, F.K. Hare, étudie les possibilitiés de réchauffement climatique résultant des rejets continuels de CO_2 dans l'atmosphère, ainsi que les incidences que ce facteur risque d'avoir sur notre économie. On peut ainsi prévoir que dans un siècle, le climat du sud du Manitoba ressemblera au climat actuel du Minnesota méridional et que les banquises de l'Arctique auront fondu. Ces facteurs risquent d'avoir des répercussions considérables sur la production agricole du Canada et sur la navigation dans l'Arctique. Hare insiste cependant sur le caractère aléatoire de ces effets, car il estime que si certaines prévisions façonnées à partir de modèles climatologiques se réalisent, elles n'impliquent pas un désastre inévitable, mais elles nous engagent à envisager sérieusement les conséquences possibles et à chercher des moyens utiles d'adaptation aux changements éventuels. En dernier lieu, il fait observer que le "problème" du CO_2 doit être envisagé dans un contexte global, soulignant que notre participation au Programme climatologique mondial et à d'autres activités du même ordre ne s'imposent pas uniquement comme un devoir, mais comme une mesure de défense de nos intérêts nationaux.

Fisher et Koerner sont d'avis que les analyses de noyaux de glace provenant des calottes glaciaires de l'Arctique polaire peuvent livrer des renseignements précieux sur les paléoclimats. Ils constatent que les idées ayant trait à la nature des changements climatiques futurs semblent varier en fonction des "modes" scientifiques de l'époque, et insistent sur la nécessité de formuler des meilleures estimations pour faciliter l'élaboration de programmes d'intervention d'urgence permettant de faire face aux changements éventuels. L'analyse de leurs données sur l'évolution passée laisse prévoir un prolongement de la tendance actuelle au refroidissement (entraînant une baisse annuelle de la température de l'ordre de 0,5 à 1,0 °C) jusqu'en 1990 ou plus tard. Ces prévisions ont une importance considérable pour les personnes ayant des intérêts dans la navigation dans l'Arctique canadien. Actuellement, les auteurs se montrent sceptiques à l'égard des prévisions fondées sur les facteurs anthropiques (dont le CO_2). Ils estiment que les prévisions portant sur le réchauffement causé par le CO_2 devraient être ajoutées aux conclusions sur la température inférées des données fossiles telles que les leurs, afin de permettre des prévisions plus réalistes sur les changements climatiques dans l'Arctique canadien.

Dans le cas des prévisions portant sur des systèmes naturels aussi complexes que le système biosphère-océans-atmosphère, le manque de connaissances détaillées sur les mécanismes (par exemple le cycle du carbone) risque de fausser sérieusement les résultats. Il est permis de penser que des effets tampon dont on n'a pas encore tenu compte dans l'ensemble du système pourraient atténuer considérablement le réchauffement imputable au CO_2. L'avenir nous le dira!

Quelles conclusions les données glaciologiques nous permettent-elles de tirer au sujet des conditions atmosphériques du passé? Bea Alt explique que le rapprochement des données tirées de l'étude des noyaux de glace de l'Arctique polaire canadien (tels que ceux de Fisher et Koerner) et d'une série de tableaux synoptiques du même genre basés sur des classifications synoptiques relativement simples permettra de tirer certaines conclusions au sujet des climats qui se sont succédé dans la région au cours des 5,000 dernières années. C'est ainsi que les tableaux synoptiques dressés à partir des conditions climatiques extrêmes qui règnent actuellement dans l'archipel des îles Reine-Elizabeth peuvent permettre d'évaluer l'ampleur des variations climatiques observées entre 1961 et 1977 et les périodes "critiques" (par exemple la courte période glaciaire et la période chaude du Moyen-Age). Rien ne permet cependant d'affirmer que les modèles synoptiques étudiés soient les seuls qui aient pu provoquer les changements de température inférés des données relatives aux isotopes d'oxygène contenus dans les noyaux de glace. Il convient de souligner que la méthode Alt appliquée à cette étude pourrait être étendue à d'autres paramètres tels que les variations saisonnières dans la glace de mer, la flore ou la faune.

Toujours sur la question des glaces, John Newell s'est appuyé sur un long et minutieux examen des données disponibles pour démontrer que les conditions glaciaires de la mer du Labrador étaient nettement plus rigoureuses au XIX^e siècle que les conditions normales actuelles, et que les conditions de près de la moitié de cette période étaient plus rigoureuses que les conditions extrêmes de la période actuelle. La sévérité des conditions glaciaires dans la mer du Labrador au cours de la période de 1810 à 1819 confirme les conclusions auxquelles Faurer est arrivé pour le détroit d'Hudson durant cette période (voir également Catchpole et Ball 1981, Figures 8, 9). Newell poursuit actuellement une enquête sur les rapports entre les variations des conditions glaciaires dans la mer du Labrador au XIX^e siècle et les variations des conditions climatiques.

Les provinces des Prairies subissent périodiquement de longues périodes de sécheresse qui peuvent avoir d'importantes répercussions socio-économiques. Pour contribuer à la compréhension de ces conditions, Street et McNichol présentent une étude systématique sur l'humidité du sol dans cette région de 1925 à 1980. Leurs analyses pour chaque décennie de cette période révèlent une variation sensible de l'humidité du sol, tant dans l'espace que dans le temps. Elles montrent aussi, de 1971 à 1981, un déplacement vers l'ouest des valeurs minimales, du sud-est de la Saskatchewan au sud-ouest de cette province et au sud de l'Alberta. Quelles furent les causes climatiques de ce phénomène? De toute évidence, il faudra des études plus approfondies pour mieux comprendre les caractéristiques des provinces des Prairies en matière d'humidité du sol et de sécheresse. Il importe de s'attaquer à cette tâche d'envergure car nos steppes sont le "grenier" de la nation. En outre, la production de la région, à cause de son importance pour les exportations mondiales, peut avoir d'importantes conséquences géopolitiques.

En Amérique du Nord, l'une des principales sources d'information sur la paléoclimatologie est la masse de documents (registres de postes, journaux de bord et relevés faits avec des instruments) que renferment les archives de la Compagnie de la Baie d'Hudson, à Winnipeg. Nous sommes fort reconnaissants à Alan Catchpole, à Tim Ball, à Cynthia Wilson et à leurs collègues qui, durant plusieurs années, ont laborieusement dépouillé ces documents. Dans le présent volume, Cynthia Wilson analyse les températures relevées sur la rive orientale des baies d'Hudson et James pendant la période exceptionnellement froide allant de 1814 à 1821. Les documents à l'appui laissent croire que ces premiers relevés de températures pris à la rivière de la Baleine, à la Big River et à la rivière Eastmain, une fois convenablement étalonnés, sont d'une valeur comparable aux séries de températures enregistrées à notre époque dans cette région. Comme Newell, le Professeur Wilson constate que la période en question fut généralement plus froide que de nos jours, et qu'au cours des étés de 1816 et de 1817, il a fait plus froid que jamais à notre époque. L'étape suivante de l'étude consiste à établir une climatologie détaillée de cette période et à la comparer avec le climat qui y règne de nos jours.

Tim Ball voit d'un oeil aussi optimiste la qualité et la valeur des anciens relevés de température effectués avec des instruments sur le littoral ouest de la baie d'Hudson. Après avoir vérifié la précision des relevés faits à York Factory et à Churchill Factory, il en énumère les principales caractéristiques et compare les températures aux moyennes récemment enrigistrées à Churchill. À York, qui compte le plus grand nombre de relevés faits avec des instruments, on découvre, à partir de 1774, deux périodes sans relevés de températures: 1814 et 1816. Ironiquement, ces lacunes sont peut-être attribuables à des conditions atmosphériques si mauvaises qu'on estimait plus important de survivre que de tenir des relevés! Ces remarquables archives de la Compagnie de la Baie d'Hudson seront assurément plus estimées lorsqu'elles seront mieux connues.

L'étude des anneaux des bois anciens peut aussi fournir des données paléoclimatiques. Parker, Bramhall et Johnson, qui traitent de la même portion du littoral ouest de la baie d'Hudson que Ball, montrent que, même si leur dendrochronologie pour la région de Churchill ne remonte pas au-delà de 1870, du bois flotté recueilli sur des plages surélevées, plus loin au sud, à la rivière Owl, permet de remonter jusqu'à 1656. Parker *et al.* démontrent qu'on peut faire des recoupements entre des sites dendrochronologiques situés à 965 km l'un de l'autre, en comparant des épinettes noires du fleuve Churchill (Manitoba) et des épinettes blanches du lac Cri (Québec), sur le littoral opposé de la baie d'Hudson (voir Parker *et al.* 1981, p. 129). En ce qui concerne les interprétations paléoclimatiques, les auteurs concluent que l'épaisseur maximale des cernes correspond le mieux à la température d'août. Il est très intéressant de penser qu'il sera peut-être possible de faire remonter à des milliers d'années les données dendroclimatologiques en examinant des bûches de bois flotté progressivement de plus en plus vieilles sur des plages plus surélevées, plus loin à l'intérieur des terres.

Au moyen de nombreuses cartes résumant des données tirées de 43 diagrammes sur le pollen daté au radiocarbone, Webb, Richard et Mott expliquent l'évolution de la végétation du sud du Québec au cours de l'Holocène. De 10,000 à 6,000 B.P., des bois de trembles, puis des forêts d'épinettes, de sapins et de bouleaux remplacèrent la végétation non arborée qui recouvrait le nord de la mer Champlain, il y a 10,000 ans. Ces forêts se déplacèrent vers le nord jusqu'à 6,000 B.P. Des forêts riches en pins pénétrèrent dans la région à partir du sud-est, en 9,000 B.P., y proliférènt vers 8,000 B.P., puis cédèrent sensiblement la place à des forêts mixtes. La pruche était déjà très répandue dans le sud en 5,000 B.P., se raréfia vers 4,700 B.P. et réapparut en force après 3,000 B.P. En plus de noter l'assymétrie prononcée qui caractérise l'histoire végétale de la région au cours de l'Holocène, les auteurs soulignent que l'Holocène inférieur fut peut-être plus sec que l'Holocène supérieur, et que le contraste saisonnier fut plus fort dans l'Holocène inférieur que de nos jours. On pourra mieux déchiffrer les facteurs climatiques et autres qui régissaient les changements de végétation observés, lorsque cette découverte sera placée en regard d'observations similaires portant sur des régions adjacentes.

Pour conclure, mentionnons que la quatrième réunion du programme d'étude des changements climatiques du Musée national des sciences naturelles (et sa première réunion internationale), consacrée aux périodes critiques de l'histoire climatique de l'Amérique du Nord durant le Quaternaire, aura lieu à Ottawa, les 19 et 20 mai 1983. J'espère que cette réunion donnera aux participants, qui représentent diverses disciplines, l'occasion d'observer et d'expliquer d'anciens événements climatiques comme l'Hypsithermal, la courte période glaciaire et "l'année sans été" (1816). En outre, je signale avec plaisir qu'Anne Smithers, une contractuelle, a terminé les annotations et l'index d'une bibliographie annotée des changements climatiques survenus au Canada pendant le Quaternaire. Nous comptons faire paraître cet ouvrage en 1984.

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FUTURE CLIMATE AND THE CANADIAN ECONOMY[1]

F. Kenneth Hare[2]

INTRODUCTION

Here in Regina in mid-March, 1981, the soil is dry and bare as a warm winter nears its close. Farmers and scientists are uneasy, because they know that the snow-free Prairie soils are vulnerable to the strong winds of spring. There is no snow-cover from the tree-line north of Saskatoon to the Texas Panhandle in the south. Western Canada has had no winter, as that term is usually understood. Neither has the western United States. For the second successive winter the climate has been anomalous over much of North America.

Yet I doubt whether this strange winter is really evidence for changing climate. The existing climate is capable of extraordinary variability, as droughts of the 1930s and 1960s showed. We can speak of climatic change only if there is a real and lasting shift in the mean precipitation or temperature, or in the probability of extremes such as we are now witnessing. Figure 1 shows the distinction. Big though the worldwide anomalies of the past decade have been, I suspect that they can all be regarded as parts of the existing climate. They are not very different from big anomalies in the past.

Scientific opinion is nevertheless tending to the view that true climatic change is just around the corner, and is indeed in slow progress already. This change is expected to come from the rapid increase of carbon dioxide in the atmosphere, together with a parallel increase in other radiatively active gases such as nitrous oxide and synthetic halocarbons. These effects are the result of human interference - of fossil fuel burning, of forest decrease, of the wastage of soil humus, of increased fertilizer use, and of the release of industrial pollutants. They will work towards a substantial warming at the earth's surface, in the view of many authorities. Others have argued that their impact may be lessened or

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[1] Ed. note: This is the extended, revised text of the Keynote Address, Seminar on Climatic Change, Canadian Council of Resource and Environment Ministers, that was presented in Regina, Saskatchewan, March 17, 1981.

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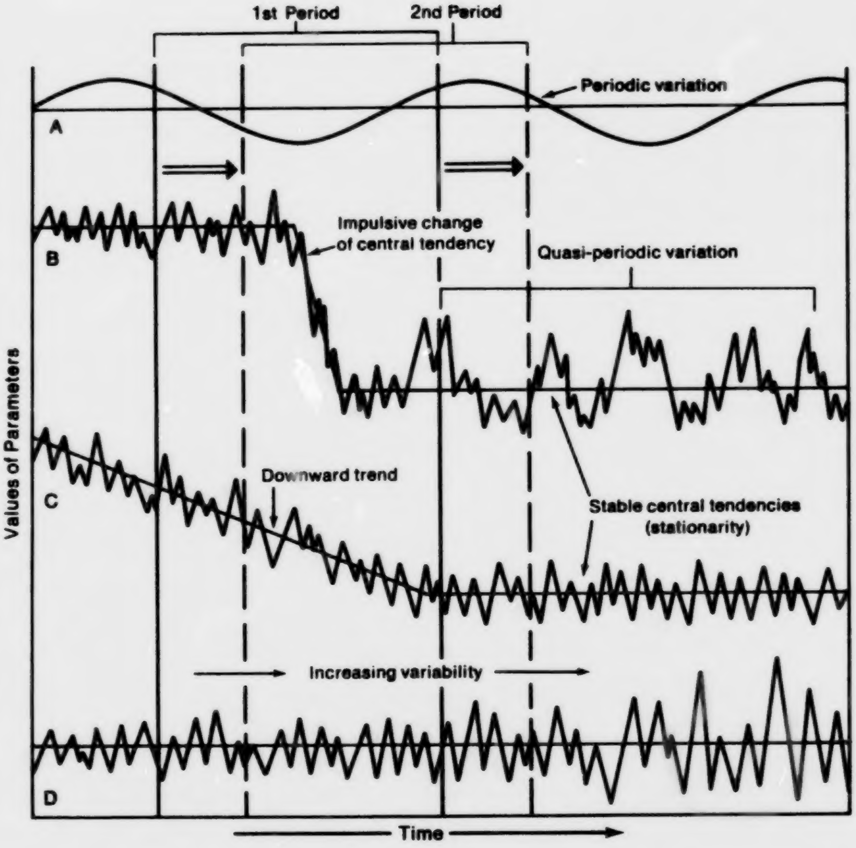
1st Period
2nd Period
Periodic variation
A
Impulsive change of central tendency
B
Quasi-periodic variation
Values of Parameters
Downward trend
C
Stable central tendencies (stationarity)
Increasing variability
D
Time

FIGURE 1: *Schematic examples of variation of climatic elements with time. Climate is averaged over successive, advancing periods, as shown by vertical bars. Climatic change is present only if there is a significant change of central tendency, or variability, or both.*

even overruled by a build-up of particles in the atmosphere from increased volcanic activity, or from smoke or soil deflation. The majority of competent scientists favours the carbon dioxide effect and hence a warming.

THE POTENTIAL WARMING: THREAT OR OPPORTUNITY?

The rise of carbon dioxide (CO_2) concentration in the atmosphere is unmistakably real, and quite rapid. If it continues it will affect world climate, and hence agriculture, fisheries and forestry. Northern countries like Canada will be among the most affected.

It is not clear whether this impending change will adversely affect human society. Conceivably there may be a net gain. All environmental change is not bad. But with the gloomy pessimism so typical of our times we usually speak of a carbon dioxide problem; we see it as a threat to our well-being. The widely circulated White House document *Global 2000* says that:

> "... a widely held view is that *highly disruptive effects* on world agriculture could occur before the middle of the twenty-first century." (Council for Environmental Quality and Department of State, U.S.A. No date; italics are mine)

After noting that a doubling of CO_2 might be reached within that period, or conceivably before, and that this might induce a 2-3°C temperature rise around the earth, *Global 2000* continues:

> "Agriculture and other human endeavours would have great difficulty in adapting to such large, rapid changes in climate."

This judgement is typical of environmentalist opinion, which stresses the negative effects of human technology. The pessimism is not shared by most students of world agriculture. Wittwer, for example, points out that the prosperous Corn Belt state of Indiana has seen a rise of 2°C during the past century, and that from 1915-45 farmers experienced an average increase of 0.1°C per year - which is about twice the expected CO_2 effect. After reviewing what is known about the impact of varying CO_2 concentrations on photosynthesis, crop productivity, water use and farm practice, he (Wittwer 1980) concludes that:

> "U.S. agriculture and its research establishment can cope with and perhaps even improve during climate change. History demonstrates agriculture's resilience to change.... The surety of climatic change should, however, force a major research initiative using genetic resources, chemical treatments, and management practices to alleviate climatic stresses on renewable resource productivity."

Canadians need to have an opinion about this controversy, for our country is among the most environmentally sensitive. Our agriculture, forestry and fisheries are practised close to their cold northern limits. Our energy consumption is heavily dependent on climatic extremes, as is our transportation system. Access to our northern shorelines and channels is severely restricted by persistent sea ice. It is in our latitude range that the CO_2 effect is expected to be most pronounced. And, per citizen, we make what may be the largest contribution to the release of CO_2 to the atmosphere. We are simultaneously among the largest culprits and the most likely victims - if that is the right word for the outcome.

It is conceivable, to go a little further, that the climate of southern Manitoba a century from now may resemble that of southern Minnesota today. Southern Saskatchewan's may be like that of present-day South Dakota. Pack ice that seals off the Arctic channels, and separates our coastline from that of Siberia across the Pole, may have weakened or disintegrated. Potential fishing grounds on both east and west coasts may have changed fundamentally. The key word in each case is "may". These are the consequences of model predictions of future climate. By no means do they imply inevitable disaster. But they do suggest that we ought to search promptly for useful ways of coping with the changes.

THE EVIDENCE FOR CO_2 INCREASE

Atmospheric CO_2 content is usually measured in terms of its concentration relative to all other gases in parts per million by volume (ppmv). Though there are large diurnal variations near the ground (because of the action of green plants or fuel consumption), the gas is well mixed in the lower atmosphere. Concentrations are much the same at all levels in both hemispheres. Present annual average values lie near 340 ppmv (using the 1974 calibration scale for the analysers in standard use). Figure 2 shows how concentrations have changed since serious monitoring began in 1958. An unsteady but persistent increase from year to year is true of all stations, including the former Canadian Ocean Station Papa, far out in the Pacific (Pearman, No date).

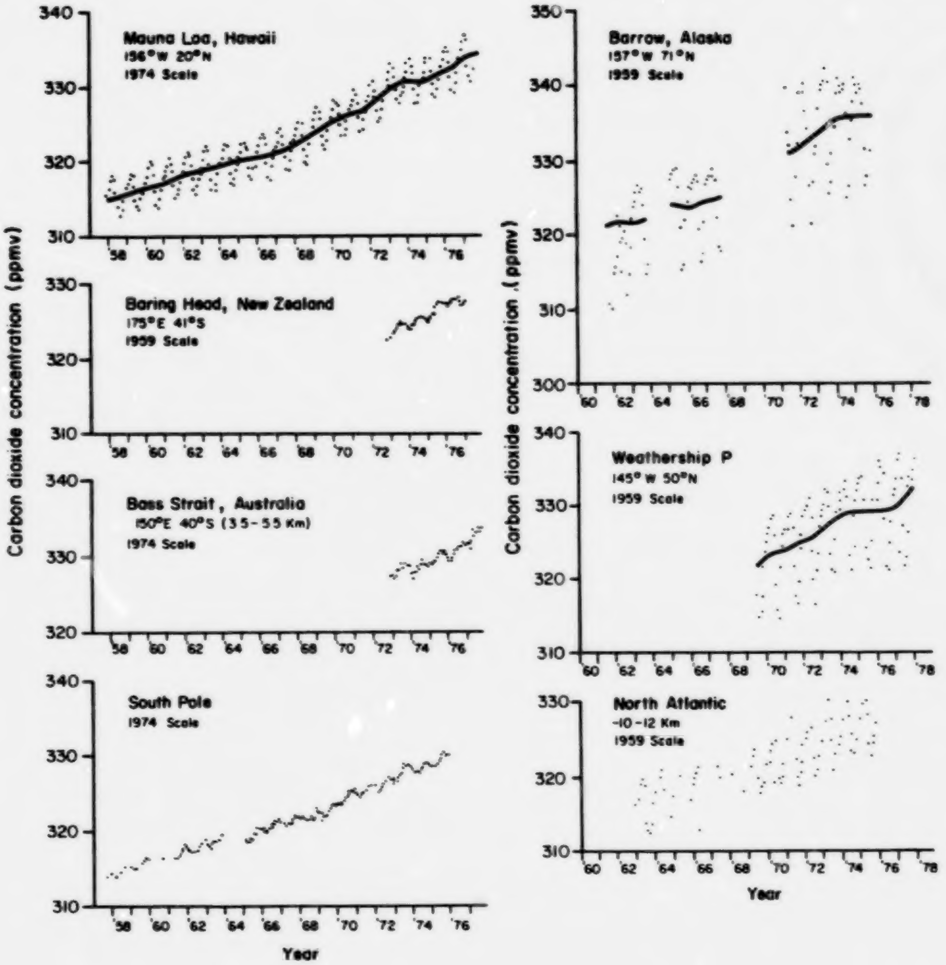

FIGURE 2: *Trends of carbon dioxide concentration in the past two decades. Two calibration scales are used, the 1974 scale being slightly above that of 1959. All records display the upward trend referred to in the text. The seasonal variation is pronounced in the northern hemisphere, but largely suppressed in the southern. Data from Pearman (no date) and World Meteorological Organization (1979).*

Unfortunately we have no systematic records prior to 1958, so we do not know when the increase started. Pre-industrial atmospheric CO_2 was probably in the range of 270-300 ppmv. If we assume that in 1880 the concentration was near 290 ppmv, the subsequent increase has been about 50 ppmv, an average of 0.5 ppmv per annum. At Mauna Loa Observatory in Hawaii, the annual increase since 1958 has varied from 0.5 ppmv in 1962-63 and 1974-75 to 2.2 ppmv in 1972-73. Similar variation affects the other stations. The recent rate of increase is clearly higher than earlier in the century, but has itself fluctuated considerably. During the 1970s, the increase has been at the rate of 3.8% per decade. Few planetary environmental changes of such magnitude have been actually measured (World Meteorological Organization 1979).

Since the mass of carbon in the planet is virtually constant, the increase must be coming from another storage reservoir. Figure 3 shows an estimate of the identified reservoirs and transfer pathways, with storages and transfer rates in gigatonnes (10^{12}kg C) of carbon or gigatonnes (Gt) per annum (Gt a^{-1}). The atmospheric store in 1980 is roughly 720 Gt, as against 610 Gt in 1860. Three net transfers are indicated:

(1) addition to the atmosphere of 6 Gt a^{-1} due to the combustion of fossil fuels (coal, oil, gas and peat), whose storage exceeds 5,000 Gt.

(2) addition to the atmosphere of 0 to 2 Gt a^{-1} of carbon from the oxidation of plant tissues, litter and soil carbon, due mainly to deforestation. Total storages are assumed to be 590 Gt living biomass, 60 Gt of litter and 1670 Gt of soil humus. Photosynthesis and respiration are assumed equal at 63 Gt a^{-1}.

(3) net transfer from the atmosphere to the oceans of 4 Gt a^{-1} of carbon (as the difference between very large two-way exchanges) (U.S.Department of Energy 1980A).

These crude estimates suggest an annual increase of 2-4 Gt carbon in the atmosphere. Recent observed increases are equivalent to a little under 3 Gt a^{-1}. Hence the additions under (2), or transfers to the ocean under (3), may require amendment, since the

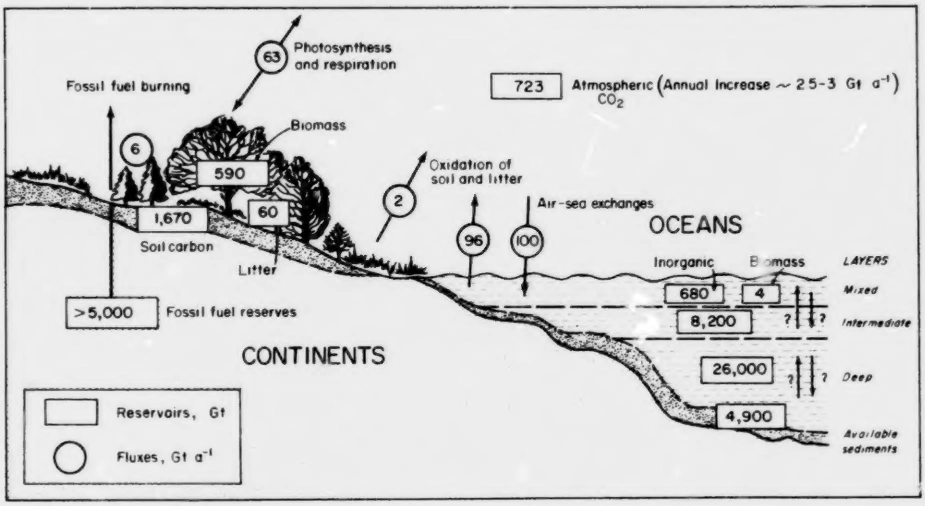
63
Photosynthesis and respiration
Fossil fuel burning
723
Atmospheric CO2 (Annual Increase ~ 2.5-3 Gt a⁻¹)
Biomass
6
590
Oxidation of soil and litter
1,670
60
2
Air-sea exchanges
96
100
OCEANS
Soil carbon
Litter
Inorganic
Biomass
LAYERS
680
4
Mixed
>5,000
Fossil fuel reserves
8,200
Intermediate
CONTINENTS
26,000
Deep
4,900
Available sediments
Reservoirs, Gt
Fluxes, Gt a⁻¹

FIGURE 3: *A sketch of the main storage reservoirs and transfer processes in the carbon cycle. Data modified from U.S. Department of Energy (1980A).*

fossil fuel consumption of (1) is considered to be reasonably accurate. In fact there is wide disagreement about the net transfers from living biota (Woodwell *et al.* 1978; Bolin 1977), from soils (Buringh 1979) and into the ocean (U.S. National Academy of Sciences 1977; Broecker *et al.* 1979). Until this is resolved by research, we have to be content with the notion that the atmospheric carbon content of 720 Gt is being added to at a rate a little below 3 Gt a^{-1}, and that this is about half the release of carbon by fossil fuel burning. The oceans are the only identified major sink for atmospheric carbon.

Efforts are being made to improve the international monitoring of atmospheric CO_2. Figure 4 shows the world network in place in December, 1979 (World Meteorological Organization 1979, see figure on p. 10). It included Ocean Station Papa, which Canada felt unable to maintain. It has been replaced by a station at Cape St. James, Queen Charlotte Islands.

WILL THE INCREASE CONTINUE?

Answers to this question obviously depend upon future use of the fossil fuels, and, to a lesser extent, future use of soil and forest resources. Present tendencies are for a shift away from efficient hydrocarbons, such as high quality crude oil and natural gas, into less efficient sources, most of all coal. If this shift continues, as sems certain, CO_2 production per unit energy produced will increase sharply. The same will be true of a shift into heavy oils, tarsands and oilshales, or into coal liquifaction. Of the available energy options, only nuclear fission (and, in the distant future, fusion), hydroelectricity and solar power offer any relief to the CO_2 build-up. These are unlikely to be effective, because they are not expected to contribute heavily to total world output of power.

Energy use, moreover, will continue to increase, in spite of price rises and political uncertainties. Annual growth in commercial world energy supply from 1890 onwards was about 5.5%, except for hesitations during the two World Wars and the slow-down of the 1930s. Because of steadily increasing efficiency, due to the shift from coal to oil and gas, the annual rate of CO_2 emission grew only at 4.3%. Neither of these figures is likely to apply in the future. The rate of expansion in energy consumption has diminished due to high prices, and the shift back to coal and away from oil will work against efficiency (Rotty and Marland 1980).

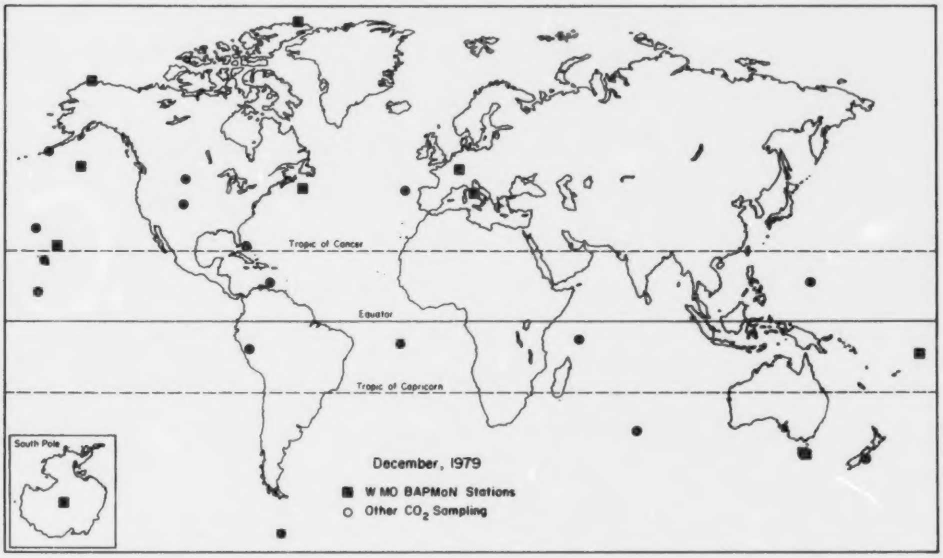
Tropic of Cancer
Equator
Tropic of Capricorn
South Pole
December, 1979
■ W MO BAPMoN Stations
○ Other CO_2 Sampling

FIGURE 4: *Network of World Meteorological Organization background air pollution monitoring stations (BAPMoN) and other CO_2 monitoring stations, as of December, 1979. After Pearman (no date).*

Various scenarios have been constructed for future fossil fuel use at selected levels of total demand. The International Institute for Applied Systems Analysis (IIASA) at Laxenburg has been most active. Their reference scenario for 2030 A.D. visualizes a total demand of 35 terawatt (TW), with fossil fuel use of 17 TW (Häfele 1980). Rotty and Marland estimate a demand of 27 TW in 2025 A.D. with fossil fuel contributing 21 TW. This would lead to carbon dioxide emissions equivalent to 13.6 Gt a^{-1} of carbon, implying an annual growth rate from present values of only 2% (Rotty and Marland 1980, p. 12) Munn *et al.* (1980) estimate a similar rate of carbon dioxide release in the year 2030. Great uncertainties attach to all such estimates, especially since the future of nuclear fission is doubtful. As recently as the summer of 1979 there was speculation that a doubling of CO_2 might occur as early as 2020 A.D. This now looks unlikely; but it is not impossible.

If these more modest estimates are realised, CO_2 levels in the atmosphere are likely to lie in the vicinity of 435 ppmv in 2025 A.D., with a wide margin of error. Figure 5 shows the Rotty-Marland estimates on various assumptions concerning the retention rate for CO_2 in the atmosphere, and for various rates of fuel consumption. It is clear that a doubling of CO_2 before mid-century is unlikely, and may not happen before 2100 A.D. Nevertheless, remaining reserves of fossil fuel are sufficient to permit four to sixfold increases in atmospheric CO_2 at some later time. It is hence important to attempt estimates of the probable climatic consequences of a doubling and a quadrupling of CO_2. A sextupling is so hypothetical that it can be ignored.

These changes will be global, since CO_2 is rapidly mixed by the wind systems, and is only slightly soluble in rain. Though the release of CO_2 to the atmosphere is strongly concentrated in the industrial regions, the effect promptly becomes global. The acid rain problem is different, because sulphur and nitrogen oxides and derived radicles are removed fairly near their sources. CO_2 increase is a truly planetary effect, and calls for international monitoring and possible action.

POTENTIAL CLIMATIC CONSEQUENCES

The climatic system involves interactions between the atmosphere, biota, soil, groundwater, seas, oceans, other surface waters, sea ice and glaciers. Through this system

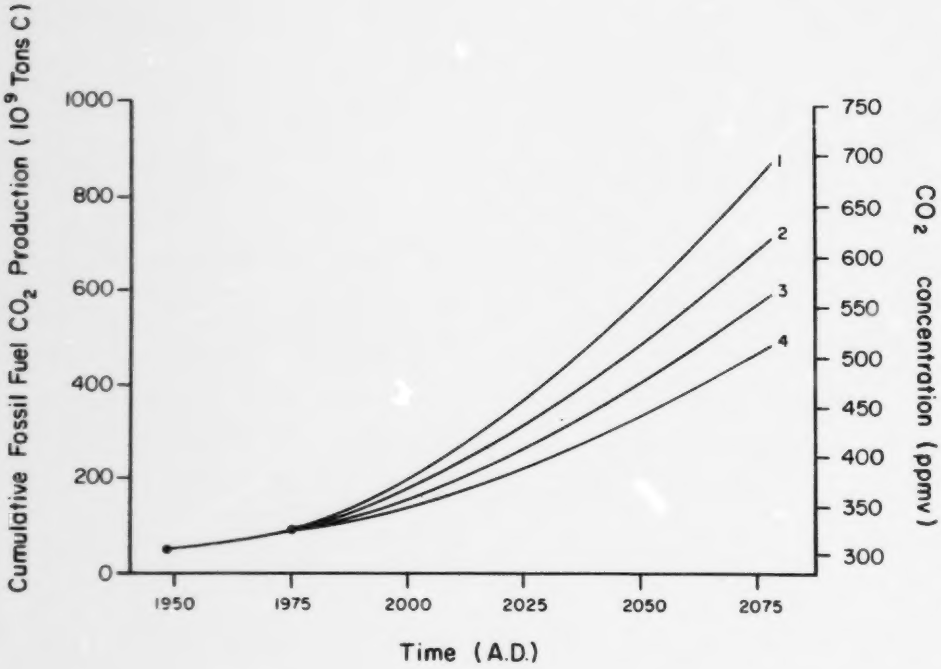

FIGURE 5: *Estimated future fossil fuel consumption and CO_2 concentrations to 2075 A.D. (after Rotty and Marland 1980). The curves show possible trends of CO_2 concentrations (right ordinate scale) as follows: Curve 2: If airborne fraction is 53.5%. Curve 3: If airborne fraction is 43.0%. Curves 1; 4: Represent 25% greater (1), or lesser (4) than the most probable value.*

pass fluxes of solar-derived energy. Within it the biogeochemical cycles redistribute materials such as carbon, water, plant nutrients and pollutants. The build-up of atmospheric carbon represents a human-induced disturbance of the carbon cycle, and hence of the energy cycle, since significant energy is required to bring about some of the transactions involving carbon (for a useful listing, see Olsen *et al.* 1980).

The build-up must also influence the temperature of the atmosphere and earth's surface. CO_2 is a gas capable of absorbing and emitting radiation at wavelengths typical of the earth and atmosphere. If CO_2 concentration increases, the atmosphere becomes less able, at a given vertical temperature gradient, to transmit such radiation. Since incoming solar radiation is largely unaffected by the change in CO_2, the effect is to raise surface temperatures, and to cool the stratosphere. The level in the atmosphere from which the radiation eventually escapes to space is also raised slightly.

To predict the consequences of this radiative change, one must take into account the redistribution of available energy by winds, and if possible by ocean currents. Early attempts to do this by means of simple one- and two-dimensional models led to the qualitative conclusion that the earth's surface would indeed become warmer if CO_2 increased, but the magnitudes varied from estimate to estimate.

The most convincing present answers are those obtained from experiments using three-dimensional general circulation models of the atmosphere (GCMs). Only a few such experiments have been conducted. Figure 6 shows the range of estimates of the change in average air temperatures over the planetary surface for various assumed values of CO_2 concentration (see U.S. Department of Energy 1980A, Figure 11.1). Obviously unanimity has not been reached, but there is a clustering of estimates near a rise of temperature in the range 2-3°C for a CO_2 concentration of 600 ppmv - assumed in the experiments to be a doubling of present values.

Only the largest computers and the most sophisticated modelling techniques can allow such calculations. One centre is well advanced towards credible answers. This is the Geophysical Fluid Dynamics Laboratory (GFDL) of the U.S. National Oceanic and Atmospheric Administration (NOAA) at Princeton, New Jersey. Manabe and Stouffer (1980) have reported an experiment in which they introduced into a 9-level GCM a realistic earth's surface - continental coastlines and topography, and an ocean with variable heat capacity (but not

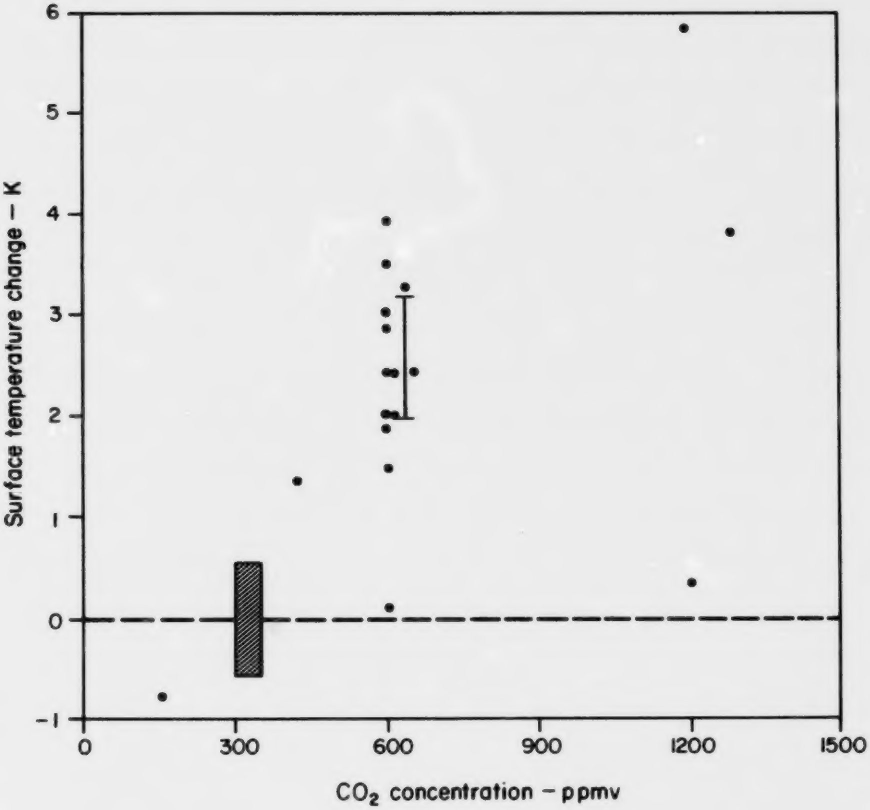

FIGURE 6: *Model calculations of temperature change associated with various assumed CO_2 concentrations (abscissa), compared with range of fluctuations associated with internal climatic variability (vertical column). Modified from U.S. Department of Energy (1980A).*

currents to redistribute heat). Cloudiness has been held locally constant, since another study (Wetherald and Manabe 1980) with simpler geography indicates that the cloud feedback process is not important. The Manabe-Stouffer study indicates the following main results:

(1) A quadrupling of CO_2 concentration should raise world annual surface air temperature by 4.5°C in the northern hemisphere and by 3.6°C in the southern. For a doubling, the likely planetary increase is about 2°C. The warming of the northern hemisphere will be greatest in early winter, and least in summer. The magnitude of the warming depends on the increased water vapour concentration resulting from the earth's surface warming.

(2) High latitude areas will be more affected than others, because the warming pushes the sea-ice limit poleward. In winter the rise of temperature in Canadian latitudes may be of the order 5-12°C, and in summer 4-5°C in each case for a quadrupling, with half these amounts for a doubling.

(3) The permanent pack ice of the Arctic Ocean and the Canadian Arctic channels will disperse if a quadrupling occurs, and will be replaced by prolonged annual winter ice of the sort now typical of large areas around Antarctica, Hudson Bay and the Baltic Sea. A doubling will reduce the thickness and extent of the permanent pack ice, but will not disperse it.

(4) A significant decrease in available soil moisture is indicated for quadrupled CO_2 in a latitude band near 45°N, due to a poleward shift of cyclonic activity, and hence of the latitude of maximum rainfall, and also a lengthening of the summer evaporation season. This is close to Canada's main belt of agriculture. Unfortunately the longitudinal resolution of the model does not reliably indicate the extent to which the desiccation will affect our farming system. It is not clear whether a doubling of CO_2 will produce similar though less

marked effects. Another Princeton study (Manabe and Wetherald 1980), with simpler geography, does indicate such an effect, and puts the most desiccated latitudes near 40°N.

These model predictions have major implications for Canada. They suggest that during the twenty-first century our agriculture will need to adapt to progressively warmer and possibly drier conditions. Navigation of our northern waters, and conditions for pipeline construction, will also change. A doubling of CO_2, probably after mid-century, will certainly have drastic effects on permafrost distribution. A quadrupling might open up navigation across the entire Arctic Ocean under conditions similar to present late summer navigation in Hudson Bay, Hudson Strait, Davis Strait and Lancaster Sound. I will return to these possibilities later.

Such dramatic changes are at present hypothetical and may never take place. It is also quite probable that the coldness of the deep oceans will delay the predicted heating by one to several decades. Some other model calculations tend to confirm the Princeton results. Multi-level GCM studies in the United Kingdom show similar rises of temperature. A marked cooling in lower mid-latitudes is, however, predicted as ice leaves the Arctic Ocean. Some studies (Newson 1973; see experiment reported in Mason 1979; see also results attributed to W.L. Gates in U.S. Department of Energy 1980A), by contrast, find little effect on atmospheric temperatures from CO_2 change.[1] Such conflicts are common in the early days of studying natural systems. They arise from the difficulty of incorporating adequate detail into boundary conditions of models, and into their systems of equations.

The extent to which such difficulties invalidate the results is a matter for expert opinion. In July, 1979, in response to Congressional inquiries, the U.S. National Academy of Sciences set up an expert panel to compare the various models. The panel had time only to compare three of the Princeton set with two models developed at the Goddard Institute for

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[1] Some simple energy balance models indicate little impact of CO_2 increase on surface temperature. GCM experiments in which sea-surface is held at present values, or constrained to rise only slowly, usually give little air temperature change for a doubling.

Space Studies, New York. Their report (U.S. National Academy of Sciences 1979) ends with the words:

> "We conclude that the predictions of CO_2-induced climatic changes made with the various models examined are basically consistent and mutually supporting .... Of course we can never be sure that some badly estimated or totally overlooked effect may not vitiate our conclusions. We can only say that we have not been able to find such effects. If the CO_2 concentration of the atmosphere is indeed doubled and remains so long enough for the atmosphere and the intermediate layers of the ocean to attain approximate thermal equilibrium, our best estimate is that changes in global temperature of the order of 3°C will occur and that these will be accompanied by significant changes in regional climatic patterns".

The only important demurrer introduced by the panel's assessment was the view, mentioned above, that cold intermediate and bottom waters of the ocean might act as slow but effective heat sinks, which would delay the atmospheric warming. Cass and Goldenberg (1981) estimate the delay at about two decades. This process, if valid, would work in the same sense as the recent lowering of estimated rates of fossil fuel consumption. Both effects would retard the anticipated warming.

Most work on these questions has ignored the possible effects of other changes in atmospheric composition. Increased nitrogenous fertilizer use may increase nitrous oxide (N_2O) concentrations in the atmosphere. It has "greenhouse" properties like those of carbon dioxide. So do many synthetic halocarbons now accumulating in the atmosphere. Preliminary attempts to estimate the thermal effects of these changes suggest that the cumulative warming induced may be of the same order of magnitude as that due to CO_2 (Ramanathan 1980). If so, the above estimates of warming may need to be raised (Kellogg and Schware 1981). On the other hand, the Bryson-Dittberner model of heat balance finds that increased dust-scattering of incoming sunlight will largely offset CO_2 warming (Bryson 1980). These countervailing opinions need to be kept in mind.

This debate has proceeded without much Canadian input. We have a GCM suitable for the purpose, and some skill in its use. But we lack both manpower and computer facilities to perform the large experiments needed to answer critical questions about our own future. Hence we have to rely, for the moment, on the exercises carried out at foreign centres.

SIGNIFICANCE FOR CANADA: (1) AGRICULTURE AND FORESTRY

Since Canada is a northern country, we might expect a high degree of adjustment to extremes of cold and inequalities of daylength. We do indeed see such adjustment in each economic sector. What will be the effect of the predicted warming on these adjustments? How can we avoid losses? Can we conceivably gain from the warming? Will the adjustment be prompt and successful, or will it be traumatic?

Agriculture is the sector where these questions arise most strongly. In spite of our northern position, agriculture and associated industries provide a livelihood to a quarter of the population, and account for perhaps 40% of gross economic activity. Canadian exports, especially of wheat, and coarse grain, are vital to the world food system. Is this large effort vulnerable to the predicted climatic changes, or do the latter offer new opportunities?

Prairie agriculture makes use of very fertile grassland soils that developed during 10,000-12,000 years of postglacial climatic history. The most productive land, given over primarily to wheat, barley, flax, oats and rapeseed production, lies in a climatically-determined arc from southern Alberta across south-central Saskatchewan into southwestern Manitoba. The northern limit of arable agriculture is determined by the rapid decrease northward of frost-free periods, and of summer warmth - in effect, of the growing season. The southern limit is set by the dryness of southeastern Alberta and southwestern Saskatchewan. This Palliser Triangle is an extension into Canada of the vast, dry High Plains of the United States, where ranching and cattle production are at home. Grain cultivation is risky, though still often practised.

The cold and dry limits of arable cultivation thus pass through our most productive land, and actually confine rich yields to a narrow belt that is climatically determined. The predicted CO_2 warming will displace this climatic belt northward. It also threatens an expansion of the dry belt into what is now the main wheat-growing area. These are obvious possibilities raised by the modelling results described above.

As we saw earlier, the warming predicted from a doubling of CO_2 is about 2 to 2.5°C in southern Canada. Such a warming would tend to shift the present favourable climates into what are now boreal forest terrain, with infertile and often water-logged soils. It would tend also to bring the detached Peace River agricultural region into direct contact with the continuously-farmed area. How long would it take for fertility of the forested land to approach that of the black and brown soils of the former Prairie grasslands? We have some experience of bringing such soil areas into cultivation. If warming occurs as rapidly as the models suggest, and if prices dictate that the forests be cleared, we shall face such conversions on a much larger scale - especially in and around the Peace River settlement, where soil conditions may be most favourable.

Much less costly would be a progressive on-the-spot adaptation of the farming system. This should present little difficulty. As was suggested above, the climate of the main farming areas of the Prairie Provinces may come to resemble that of present-day South Dakota, southern Minnesota and parts of Wisconsin. These areas support highly efficient wheat-dominated agriculture today, with some corn-belt farming in the far southeast. Growing seasons are longer than in the Canadian Prairies, and field practices and crop varieties differ. But there seems no reason to doubt that our Prairie arable belt could be readily adapted to the new climate, using the existing technology from farther south. And there is equally little doubt that the active tradition of agricultural research could cope with the impending changes by innovation and foresight.

Much the same is true of the mixed farming system of the Great Lakes-St. Lawrence Lowlands of Québec and southern Ontario. Corn-belt agriculture much like that of the mid-western United States is well established on the old lake plains of southwestern Ontario. Short season hybrid corns have permitted an extension of this belt, and a diversification of the system well into the Montréal basin. The mixed crop-animal husbandry of the region, with its cash earnings in the form of dairy produce, poultry, fat stock and specialty crops like fruit and tobacco, seems well able to adapt to the temperature changes predicted. For most of the present activities, a warming would probably bring net gains.

The prediction of reduced soil moisture availability in or about Latitude 45°N (see above), is however, disquieting. Rainfall is only just adequate in the Prairie wheat-farming areas today, and drought periodically reduces production - most recently in the growing season of 1980. Southern Québec and Ontario are less vulnerable, as is the intensive but very restricted agriculture and horticulture of southern British Columbia (where summer irrigation cushions crops against drought). In the small Atlantic Province areas of agriculture excessive rainfall is more often the problem, and a decrease might be welcome. The model predictions hence give most concern for the Prairies. As noted earlier, the longitudinal resolution of the models is too poor to say whether the most vulnerable parts of our agriculture are really threatened.

This is the qualitative assessment of a climatologist and geographer. It should be replaced by a quantitative appraisal by agricultural scientists and economists. Neither group has paid close attention to the interactions of climate and agriculture. At the World Climate Conference of 1979 it was difficult to persuade any major figure to undertake such a study. Those who eventually agreed did an outstanding job of illustrating on a world basis the importance of climatic variability in agricultural systems. But climate is not a large agenda item for most serious students of agriculture (Hare 1981).

Much the same is true of forestry. Qualitatively the changes in Canada's climates foreshadowed by the models should favour forest increment, and hence the health of the industry. A possible exception is the hypothesized soil moisture loss in mid-latitudes, which may presage greater fire risk. Another may be changes in snowcover and hydrological régimes of the forested watersheds. The relationship between climate, forest increment, fire, disease and other variables is not close enough or well enough known for a clear verdict. But forest production methods will certainly have to take account of such changes, if they occur.

Forestry and agriculture - major sectors of our economy - are both climate dependent. Both relate to the bioclimate, an aspect of climatology that receives far too little attention in Canada. Attempts are now under way to assess Canada's biomass resources in relation to energy production. Understanding the way in which crops and natural vegetation capture solar energy and make it available is a proper activity for climatologists as well as plant physiologists and ecologists.

SIGNIFICANCE FOR CANADA: (2) NORTHERN DEVELOPMENT

A second broad national sector that is heavily dependent on climate is northern development, in its broadest sense. All economic activity in arctic and subarctic latitudes has to be closely adapted to climate. This is obviously true of the indigenous native hunting economies now in drastic decline. It is even truer of such externally-inspired ventures as oil and gas development, pipeline construction, the navigation of ice-choked seas and the use of the northern seafloor. All these things will be much affected by predicted changes.

The predicted warming is much stronger in high northern latitudes than in those of southern Canada, and greater in winter than in summer. Annually, in the latitude belt 60-80°N, increase of temperature due to doubled CO_2 may be about 4°C, with winter increases of perhaps 6°C.[1] There is much uncertainty about these figures, because they depend on an accurate modelling of the effect of the general warming on the distribution of sea ice and snow. As the latter retreat poleward, opening up darker water or land surfaces, more solar radiation is absorbed and less is reflected. This acts as a positive feedback. The models incorporate this process in a crude way, and do so for a much-generalized earth. In actuality, Canada's Arctic is a very special area, with narrow marine channels and land-locked seas alternating with land areas, some of them mountainous. All that can be said with some assurance is that a general warming, if it occurs, is likely to affect northern Canada more strongly than the south. Details are quite unpredictable.

One effect of the predicted warming should be a major change in permafrost stability and distribution. Permafrost underlies much of the soft terrain of the lower Mackenzie Valley and delta, and extends beneath the floor of the Beaufort Sea. It is general in the arctic islands, and occurs widely and discontinuously in tundra and northern boreal forest environments of Québec, Labrador, Ontario, Manitoba, Mackenzie, Keewatin and the Yukon Territory. Rises of temperature of the magnitude predicted would result in the slow but irreversible melting of much of the discontinuous permafrost, and probably the northward retreat of the zone of continuous permafrost. Canada now has an increasingly sophisticated and efficient set of engineering techniques with which to tackle such problems. Nevertheless the impending changes have significant implications for the use of overland vehicles, construction equipment, pipeline design and building construction. There is no reason to doubt that we can find technical solutions, as long as we are aware of the environmental change.

The ice that so badly impedes navigation and hinders undersea exploration is another element that is bound to be affected by CO_2 warming. The sea ice responsible is of three main kinds. The Arctic Ocean beyond our shores is covered with permanent pack-ice 3-4 m thick with ridges to over 10 m thick. Summer melting is only partial, and the pack thickens again each winter. This pack-ice permanently threatens the Beaufort Sea. Some of its fragments drift into and block the northern passages of the Arctic Archipelago. Such old ice occasionally drifts into Baffin Bay. The second type is annually-formed ice in the channels and seas of Arctic Canada, including Hudson Bay, Foxe Basin and Davis Strait. Most of the drifting pack-ice of the Labrador Current is made up of such one-season ice. The third component is glacial ice from Greenland, which drifts southwards as bergs in the Canadian and Labrador currents, ultimately reaching the shelf seas off Newfoundland, where the bergs pose problems for oil and gas exploration as well as for navigation. The ship *Titanic* was one victim of such bergs.

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[1] These are half the Manabe-Stouffer estimates for a fourfold CO_2 increase (Manabe and Stouffer 1980). Since the fourfold case involves an ice-free Arctic in summer, and the twofold case does not, the assumption that $dT/d(CO_2)$ is linear may be invalid.

Present climatic variability already produces years of good and bad navigation in the Arctic seas. In some summers ships can penetrate deeply westward into the channels beyond Lancaster Sound and Barrow Strait. Baffin Bay clears of ice. In other years, heavy ice blocks all the narrower channels, and even the open seas - Baffin Bay, Hudson Bay, southern Beaufort Sea - are hard to penetrate until late August or September. In the 1970s there were several difficult summers. These large variations have given us considerable experience of the effect of variable climate on sea-ice conditions, though a time-lag is invovlved; ease of navigation is not simply due to an unusually warm summer. Even the most favourable conditions experienced now do not, however, come close to what might be expected from a CO_2 warming. Much easier ice conditions should eventually result. This has an obvious bearing on long-term strategies for the use of the northern seas and channels, as regards both navigation and seafloor development.

Two myths need to be queried. One is that a doubling of CO_2 would result in dispersal of the permanent pack-ice of the Arctic Ocean. There is evidence that such a clearance has not occurred for 700,000 years (Hare 1979).[1] During that long period there have been several epochs with higher temperatures than a doubling of CO_2 could account for. And the

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[1] Ed. note: A review by Clark (1982) places the time of origin of the ice-cover between 5 and 0.7 M yr ago.

Manabe-Stouffer model now suggests that a fourfold-increase of CO_2 would be needed to achieve dispersal of the pack, a result consistent with the arguments of Flohn (1979). Such an increase is unlikely in the next century, but could, according to some scenarios, occur towards its end. Possibly, in the very long term, Canada may no longer be separated from the Soviet Union by a thick pack-ice sheet (the nearest thing to a polar "ice-cap" that this hemisphere has). Navigation in the north, and undersea technology, will then have to cope only with annually-formed winter ice. We have experience of such conditions in Hudson Bay, Foxe Channel and Hudson Strait (where a few bergs creep in, too). Technically they can be readily coped with, though not without considerable costs. It is less easy to persuade marine insurers to cover general shipping in such waters, a problem that has long plagued the Hudson Bay route.

A second fallacy is that the warming poses the threat of a large and rapid rise of sea-level due to melting of the polar ice-caps. The northern hemisphere has no such cap. It has only a thin layer of floating sea ice, whose total dissolution would have little or no effect on sea-level. Only substantial net melting or "calving" of the Greenland and Antarctic glaciers (ice-sheets) can raise sea-level. Warming on the scale predicted due to CO_2 increase would indeed melt back the lower edges of these ice sheets, but increased snowfall on their higher slopes would partially offset the process. It is barely possible that the so-called West Antarctic ice may be unstable, and may disperse mechanically into the world ocean. This would lead to a rise of sea-level of up to 5m; but the effect is highly improbable. Much more likely is an acceleration of the present rise of world sea-level (10 cm in the past century). A rise of 60 cm in the next century might be realized.

SIGNIFICANCE FOR CANADA: (3) ENERGY POLICY

Since the main source of added CO_2 in the atmosphere is the burning of fossil fuel, obviously energy policy must take the situation into account. Two questions arise. Will the anticipated warming alter energy consumption significantly? And will demand for control of CO_2 emissions affect choice of energy options?

The first question seems straightforward. A 2 to 3°C rise in mean annual temperature will decrease heating degree days by about 11 to 16%. Space heating requirements will decrease more or less proportionately. There may be other and smaller adjustments in transportation energy costs, and in industrial process energy. But the main effect should be due to the decrease in space heating costs. This will be partly offset by a significant increase in air conditioning costs during summer. The effect is to give Toronto the present climate of Columbus, Ohio, or Winnipeg that of Minneapolis.

The second question is far more complex. Canada has the world's highest *per capita* consumption of energy, and in spite of recent efforts at conservation, the energy needed to generate each unit of gross domestic product (GDP) has not decreased significantly since 1950 (Minister of Energy, Mines and Resources, Canada 1973). During the same period, consumption per unit of GDP has decreased in many industrial countries - notably in the U.K. and France (Dunkerley 1980). Pricing policies in Canada have not encouraged conservation until very recently. It is reasonable to expect that consumption of fossil fuels will remain very high. Clean sources of power (as regards CO_2 emission) contribute about a quarter of our consumption. The rest comes from oil, gas, coal and wood, all of which add CO_2 to the atmosphere. Moreover the shift toward heavy oils, tarsands and coal envisaged in the 1980 National Energy Program as part of the drive towards self-sufficiency must accelerate the rate of CO_2 release per unit energy produced.

CO_2 concentration over Canada does not, however, depend at all closely on local energy consumption. The gas is diffused globally by the winds. Hence a unilateral decision on our part to restrict the use of carbonaceous fuels would not produce local benefits. At best it would have only a small but measurable effect on the worldwide concentration. Local and national decisions on the type of fuel used have a marked bearing on local air pollution problems, and such regional problems as acid rain. But they are futile in the control of CO_2 build-up. The possibility that control measures may be sought internationally means we must remain alert to the implications of heavy fossil fuel and synthetic fuel use.

CONTROL MEASURES

Though it has not yet been demonstrated that CO_2 increases will be on balance harmful to man, possibly the world will decide that the risk is too great to take. In such a case, international action to contain the problem may be sought. The fact that CO_2 emissions come mainly from advanced industrial powers makes such action conceivable. Agreement between the U.S., U.S.S.R. and European Economic Community would be the necessary step. It seems unlikely, however, that the world will be able to move quickly away from the fossil fuels. Restrictions on oil supply may even accelerate the use of less efficient techniques of exploitation. Hence agreement, if it comes, is more likely to focus on the possibility of control than on the abandonment of carbonaceous fuels.

The technological removal of CO_2 from flue gases and exhaust pipes is feasible, but prohibitively energy-intensive and costly. A recent analysis by the U.S. Department of Energy argues that it is feasible only in an all-electric economy, since otherwise capital investment requirements are out of the question (Albanese and Steinberg 1980). For centralized flue emissions, removal by monoethanolamine (MEA) absorption/stripping is the least energy-intensive technology available, but net power plant efficiency is reduced from an assumed 38% for zero removal to about 20% for complete removal - a huge burden. Disposal of the immense volume of carbon removed would have to be in the deep ocean, which would add further costs - and imply a threat to the ocean carbon cycle. Hence the technological "fix" appears out of the question.

Of other possible measures, only the control of biotic and soil carbon exchanges seems useful, on other grounds as well as the removal of CO_2. Attempts to increase CO_2 absorption by the oceans seems in the realm of science fiction, and are, in any case, unwise given the present unsatisfactory state of knowledge of the oceanic carbon cycle.

Present storage of carbon in the biota, chiefly in the woody stems, branches, trunks and roots of shrubs and trees, has been variously estimated from 590 Gt (estimate by Olson *et al.* in U.S. Department of Energy 1980A, Figure 5; Bolin *et al.* 1979) to 828 Gt (estimate in Woodwell *et al.* 1978), with annual exchange rates due to photosynthesis and respiration in the range 50-63 Gt a^{-1}. The storage is thus comparable with the 720 Gt in the atmosphere. Forest clearance, with subsequent use of the land for less efficient carbon storage, obviously transfers carbon to the atmosphere, chiefly due to burning (Wong 1978). A recent careful estimate puts the net transfer to the atmosphere as 0-2 Gt a^{-1} (see Figure 2; Seiler and Crutzen 1980), though much higher estimates are also current (Woodwell *et al.* 1978; Bolin 1977). Storage in soil is estimated in the range 1450 to 1730 Gt, about one quarter less than before the agricultural revolution. Present day transfers to the atmosphere are variously estimated from negligible values to Buringh's (1979) most likely figure of 4.6 Gt a^{-1}. We thus have only a hazy notion of the size of the biotic-soil reservoir of carbon, and of net exchanges with the atmosphere.

Forest clearance for agriculture and the reduction of forest biomass because of poor forestry practices, are clearly within the realm of possible management. Most of the storage is in tropical rainforest, which is being rapidly converted to other uses. However, large amounts are stored in the boreal forest (about one eighth of the world total). Overend (in Climate Planning Board, Canada 1979) has estimated that total forest storage in Canada is 44 Gt, and that a further 38 Gt are stored in the huge northern muskegs. Hence this country alone may control a surface storage of 82 Gt, or about 12% of the amount stored in the atmosphere. And this neglects possibly larger amounts stored in our soils.

One way in which nations can at least slow down the CO_2 build-up is to prevent further wastage of forest biomass. Good forest management should aim at a high level of stored biomass, or standing crop. Much forest exploitation works today in the other direction. In Canada, the biomass storage in our forests must have declined substantially since cutting began, in spite of regeneration. In the United States, this decline has been halted, and even reversed; the standing crop of merchantable timber has recently been slowly increasing (Delcourt and Harris 1980; personal communication, M. Dawson). Canada now faces an era of fully-managed forestry. Perhaps we can rebuild some of the biomass losses of the past two centuries.

It may be more difficult to reverse the loss of soil humus that affects our agricultural areas. Nevertheless every effort should be made to do so, if there is a need to slow down carbon accumulation in the atmosphere.

Though technological control of the CO_2 build-up seems impossible, there are thus avenues of land and natural resource management which Canada can follow - and which we can advocate internationally.

RESEARCH NEEDS

Clearly, the CO_2 question is still only part-formulated. In all the foregoing, the one reasonably certain fact is that atmospheric CO_2 is increasing. Most of the other estimates are crude approximations. They may well be wrong by factors of 2 or more. And most of the text was written in qualitative terms. Obviously, we need more research of an interdisciplinary kind. Reviews of what is needed have been published by the U.S.

Department of Energy (1980A,B), the Climate Planning Board, Canada (1980)[1], Williams (1978), Bach *et al.* (1980) and World Meteorological Organization (1979). Here I shall focus attention on Canada's special needs, opportunities and capabilities.

The atmospheric CO_2 question is best approached through an analysis of the carbon cycle as a whole. The effect of human action, both deliberate and inadvertent, must also be traced through the entire climatic system. Hence an interdisciplinary program involving at least atmospheric scientists, ecologists, engineers, oceanographers, soil and agricultural scientists, foresters, marine biologists, glaciologists and geochemists is needed - as is a mechanism to hold such a heterogeneous group together. If management is involved, research must extend into the social science specialisms concerned with institutional behaviour, environmental perception and economic performance. In brief, the need is for a nationally coordinated effort that can mobilize the skills needed for understanding and management.

Moreover, the Canadian national program must be closely related to the corresponding U.S. program, and to the World Climate Programme being coordinated by the World Meteorological Organization. Close liaison will be needed, too, with various energy agencies that have the CO_2 question on their agenda. The list is long.

An immediate need for all such work is that the CO_2-monitoring program be maintained. Canadian sites involved are at Alert, Northwest Territories, Sable Island, Nova Scotia, and Cape St. James, British Columbia. The closure of Canadian Ocean Station Papa was a serious blow to the national and international programs. Its replacement by a coastal station does not fully meet the need.

It will also be necessary to maintain a watch on climate itself. The natural variability of climate (the noise) is so great that slow changes of temperature and precipitation (the signal) will be very hard to detect. So will changes in sea-ice cover, which is inhomogeneous and variable in the extreme. A recent analysis by Madden and Ramanathan (1980) of temperature variability at 60°N shows that the CO_2 signal should by now be detectable, especially in summer data, where it should contribute about 29% of the total variance. In fact they could not detect a signal; a recent two-decade period was no warmer than the period 1906-1925. Because Canada covers the range of latitudes likely to be most affected, it is important that we make elaborate attempts to detect the signal due to CO_2 increase in temperature and precipitation records - and, if possible, to devise ways of separating this signal from those due to other causes.

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[1] See also, Climate Planning Board, Canada's "A Plan for Action." 22 pp.

The main goal of atmospheric research will presumably be modelling future climates by GCM techniques. The Atmospheric Environment Service GCM capability is a good foundation, but we lack computer capacity on which to design models comparable with those in use, for example, at GFDL Princeton, or at the U.K. Meteorological Office, Bracknell. We need to be able to conduct model experiments designed to answer questions special to Canada's interests. The modelling community is essentially international. There is a free flow of data, ideas and results between the small number of centres involved, including those within the U.S.S.R. Canadian scientists need to be members of this community, and to conduct their own *ad hoc* experiments. At present the latter cannot be done within the country.

Substantial work on the rôle of the oceans in the CO_2 balance is under way at the federal oceanographic institutes at Patricia Bay, British Columbia, and Bedford Basin, Nova Scotia. At the Patricia Bay Institute, C.S. Wong's laboratory is equipped for calibration and monitoring work, and maintains a close watch on relevant ocean data. Canada's seagoing vessels can and should contribute to the intense activity now in progress to clarify mixing mechanisms whereby carbon is exchanged between surface mixed layers and intermediate and deep waters. The northern seas probably play a key rôle in these exchanges.

Highly significant work is also in progress in the Plant Research Institute of Agriculture Canada, ranging from direct linkage of crop yield with variable climate to field measurement of CO_2 fluxes above growing crops and grass. There is a need for a further appraisal of the status of soil carbon in Canada, especially on the Prairies, where a run-down of humus content of about one-third since pioneer times has been alleged. In connection with model predictions of future climate it will be useful to examine the need for adaptations to the farming system - and even the location of farming - hinted at above.

Much of the necessary research on the carbon cycle must still lie, however, with the ecologist. The aim must be a full understanding of the linked carbon and energy cycles in natural ecosystems. Outstanding beginnings were made in Canada during the International Biological Programme. What was then attempted, and is still needed, is an assessment of stored carbon and of the net annual production of living tissues, in representative natural ecosystems. The Truelove Lowland Tundra Biome study, directed by Bliss (1977), produced a uniquely detailed analysis of the mosaic of ecosystems making up the High Arctic biome. Of comparable stature was the Matador Grassland Biome study directed by R.T. Coupland, which provided a similar analysis of areas of protected and grazed prairie grassland in Saskatchewan.[1] Less complete, but equally vital work on forest storage and productivity has been a research tradition of the Canadian Forestry Service, chiefly at its laboratories in Sault Ste. Marie and Fredericton, and more recently in Edmonton.

New consciousness of the energy problem has led to significant research on biomass productivity. The Canadian Biomass Program led by the National Research Council, and directed by R. Overend, is a federal inter-agency project designed to determine whether natural biomass production can contribute significantly to national energy supply after 2000 A.D. The program (planned to end in 1985) will estimate carbon storage and biomass productivity, nutrient depletion and environmental impacts, for the major ecosytems of Canada. An attempt is also being made to convert forest inventory information to biomass data, and to assess the role of the great northern muskegs. This program, if it is adequately supported, should provide many of the answers needed on biomass processes.

Canadian centres (chiefly in universities) have been active in the analysis of socioeconomic impact of climate. A leader in the field internationally has been W.R.D. Sewell (e.g. Sewell *et al.* 1973; U.S. National Science Foundation 1968) of the University of Victoria, who has concentrated mainly on weather modification programs, and on adjustment to climatic hazard. The latter has been the preoccupation of I. Burton (1980) and A. Whyte[2] of the University of Toronto. R.E. Munn and F.K. Hare of that university are involved with the scientific content of the climatic impacts component of the World Climate Programme, and especially with the impacts project of SCOPE, the relevant committee of the International Council of Scientific Unions (Munn and Machta 1979; see also Munn in Seiler and Crutzen 1980).[1]

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[1] Matador reports are numerous. See especially Redmann (1974).

[2] See also, I. Burton and A.V. Whyte, Environmental Risk Management. Wiley and Sons, Chichester (to be published).

Much useful work is thus in progress in Canada. The country does not lack in skills or curiosity. What it lacks is a focussing of effort, and adequate computer hardware. An attempt to provide the coordination and focus is being made as part of the Canadian Climate Program. Its Draft Plan (Climate Planning Board, Canada 1980) includes such a provision, but notes that ... "progress in launching a Canadian capability to understand and predict the effects of increasing carbon dioxide is slow". This review confirms the Plan's judgement.

A CAUTIONARY NOTE

This brief review of potential effects of a possible climatic change has been full of warnings that the change may never happen. Natural systems are apt to be more resilient and homeostatic than we believe. A final cautionary note is needed to reemphasize the point.

Figures 7 and 8 show long-term rainfall records from northern India (Parthasararthy and Mooley 1978), and England and Wales[2] respectively. These are estimates of spatially-averaged rainfall in areas of fairly high natural variability. They extend over periods of 120 and 250 years.

Both records show the high year-to-year variability that is typical of the rainfall record. In the Indian case, the drier years (or groups of years) represent the threat of famine, for this is the area so dependent on monsoon rainfall for its grain crops. England and Wales are less sensitive, but there, too, the drier years result in crop losses and

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[1] In the complex network of arrangements, WMO has devolved a responsibility for the climatic impact component of the World Climate Program on the U.N. Environment Programme (U.N.E.P.), which has a Scientific Advisory Committee on the subject chaired by J. Dooge. Hare serves on this committee. U.N.E.P. in return has contracted out a project on climatic impact assessment under R.W. Kates. This is administered by SCOPE, a Committee of the International Council of Scientific Unions. Kates' project also has a Scientific Advisory Committee, chaired by Hare. In spite of the complexity, the arrangements work quite well!

[2] T.M.L Wigley, J.M. Lough and P.D. Jones. Revised England and Wales rainfall series (Manuscript in preparation).

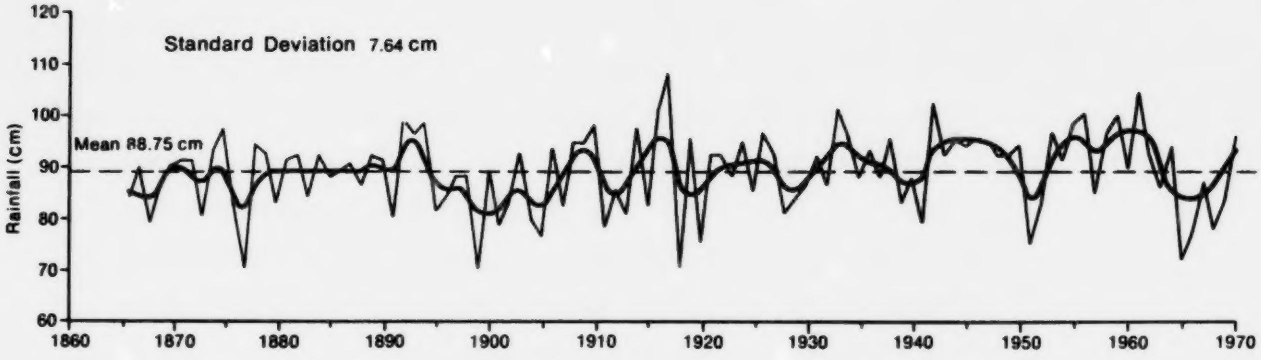

FIGURE 7: *Variation of spatially-averaged summer monsoon rainfall over India since 1866, with smoothed curve. No significant change is visible. Only a weak 2.7- to 2.9-year periodicity is present. After Parthasararthy and Mooley (1978).*

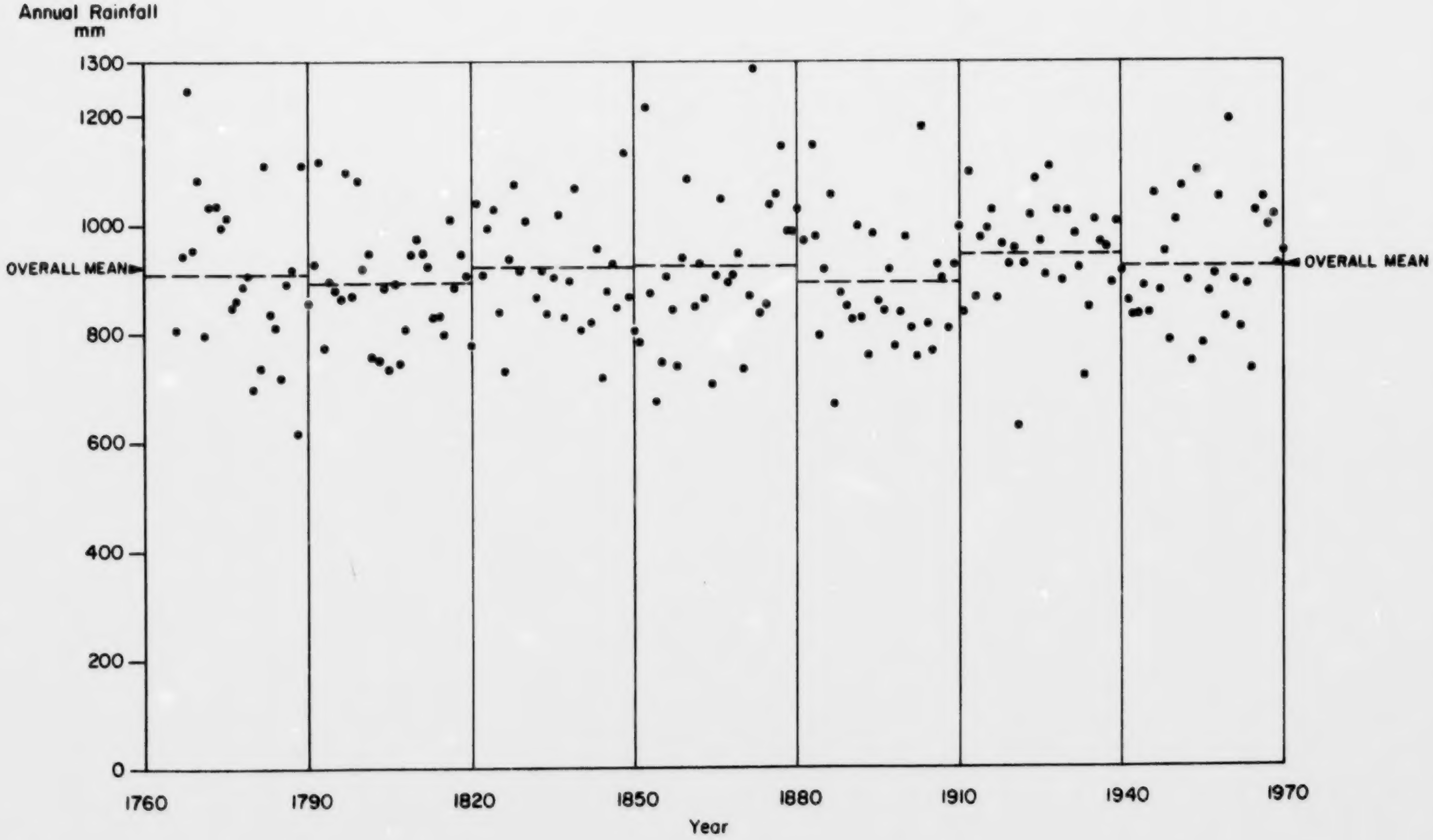

FIGURE 8: *Variation of spatially-averaged annual precipitation over England and Wales (1760-1970), with smoothed values. After Wigley* et al. *(manuscript in preparation).*

difficulties in water supply. Neither record shows a statistically real trend upward or downward. Neither shows much tendency towards periodicity. Both are typical of highly variable régimes with underlying stability.

So conceivably, the climatic system is sufficiently stable to absorb even carbon dioxide and associated effects without striking change. There may be stabilizing processes that we have not yet identified. As we saw above, the effects should already be detectable in the high-latitude belt of the northern hemisphere. In fact they are not. So a certain skepticism should be maintained.

CONCLUSION

The CO_2 question is not yet well articulated, but this much can be said: there will be benefits as well as costs for most societies. It is not clear whether Canada will lose or gain from the changes, if they eventuate. It is by no means certain, indeed, that they will ever happen. And if they do, we do not know in detail how drastic they will be, or how they will distribute themselves across the national map. All that scientists can advise at present is to be wary: the country should be on yellow alert.

This means that we should work hard to understand and predict the impending changes, and to monitor the atmosphere, oceans and biota so as to detect their progressive arrival. We should be ready with strategies to offset any hardships the changes may bring, and to exploit any opportunities created. If these things are done, Canada may, on balance, profit from the CO_2 effect.

Since this is a global problem, and since Canada's prosperity depends on foreign trade, we must also involve ourselves in international efforts to answer the same question. Participants in the World Climate Programme and similar efforts is not merely a duty; it is a defence of the national interest.

The time-scale of the impending changes is so long that they lie outside the ordinary framework of national policies and international statesmanship. If they happen, however, they may well achieve a transformation of the environment greater than anything experienced in the history of civilization. Our children and grandchildren will live through this re-ordering of the natural world. In the circumstances, the scientist is entitled to suggest that the politician listen to his advice - especially since, for once, that advice does not involve a message of inevitable doom.

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ICE-CORE STUDY: A CLIMATIC LINK BETWEEN THE PAST, PRESENT AND FUTURE

D.A. Fisher and R.M. Koerner[1]

INTRODUCTION

Research over the past 20 years (e.g. Dansgaard *et al.* 1971; Lorius *et al.* 1979) has substantiated the pioneer work of Manley (1958) and Lamb (1972) in emphasizing the variable nature of climate at almost all wavelengths. However, ideas concerning the nature of future climatic changes. unfortunately, seem to follow the trends of fashion. Experts in one decade consider we are entering an ice age, whereas those in the next believe we are due for a dramatic warming. What we, as scientists, should emphasize in this period of academic flux is that climate has changed in the past and will change in future. We must, therefore, generate our best estimates of the *degree* of climatic change that is likely to occur in the future in order to allow and encourage the development of contingency plans to accommodate all possible changes. The northern boundary of cultivable land crosses Canada from east to west. So the country is peculiarly sensitive to climatic change - especially in terms of the length of the growing season. This in turn has profound political implications, Canada being the world's second largest grain exporter.

In this paper we will outline the way climate has changed in the High Arctic over the past few thousand years, giving particular attention to the last few hundred years. Based on knowledge of the past, we will attempt to evaluate the magnitude of climatic change, extrapolate our climatic record a few decades into the future, and indicate how this might affect human development and extractive industries in the North. We consider only the natural climatic record, essentially disregarding various effects produced by people. The magnitude of these effects, termed anthropogenic, are disputed and we will mention them briefly later.

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DATA SOURCE

Our data are drawn from an analysis of four High Arctic cores taken between 1965 and 1979 (Table 1; Figure 1). These cores were drilled with a CRREL thermal drill at sites close to the tops of the ice caps, chosen so as to minimize problems due to flow of the ice itself. The climatic history deduced from three of these cores (M65, D72 and D73) has been reviewed previously (Koerner and Fisher 1981).

TABLE 1: *ICE CORES FROM THE CANADIAN ARCTIC.*

SITE	DESIGNATION	ALTITUDE (M A.S.L.)	LENGTH (M)	YEAR DRILLED	OLDEST ICE (YR B.P.[1])
Meighen Island Ice Cap	M65	268	121	1965	~ 5,000
Devon Island Ice Cap	D72	1800	300	1972	> 100,000
	D73	1800	300	1973	> 100,000
Agassiz Ice Cap, Ellesmere Island	A77	1700	340	1977	> 100,000

[1] Before Present; present considered as 1950.

Ice caps are ideal bodies for the study of climatic change, but before considering the proxy data gathered from them, a word is necessary about the mode of accumulation on ice caps.

Once snow falls on the surface of an ice cap, it begins to undergo metamorphic processes due to temperature and vapour pressure gradients that quickly transform it from a loose, low-density material of low strength to a compact, higher-density material of substantially greater strength. Burial under subsequent snows eventually transforms it, at a depth of about 50 m, to ice of a density of 840 Kg m^{-3}. At a depth of 100 m it attains a "final" density of about 900 Kg m^{-3}.

Flow paths of ice particles show an almost purely vertical (downward) component in the centre of an ice cap, a purely horizontal component in the zone where the annual accumulation rate is equal to the annual ablation rate (equilibrium line), and a vertical

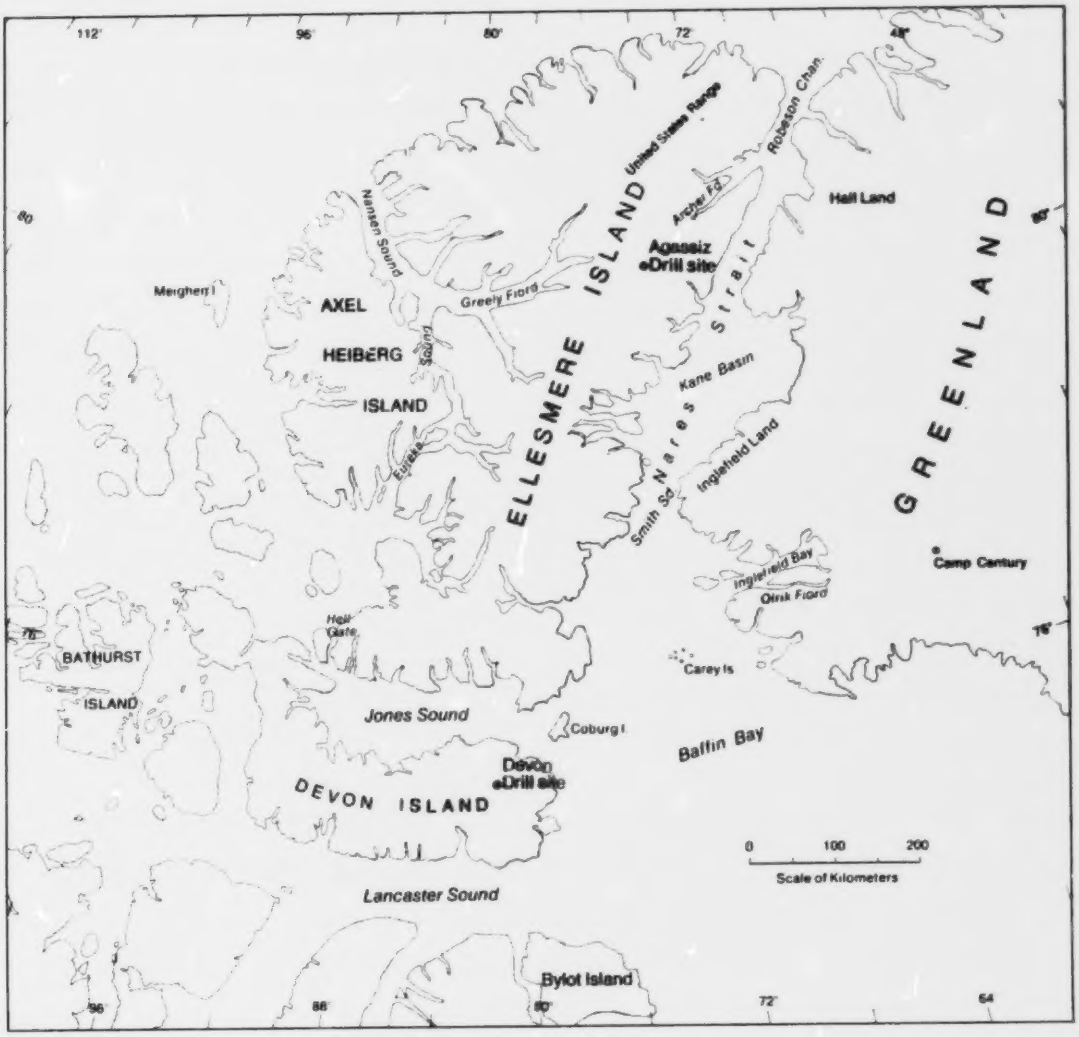
112°
96°
80°
72°
48°
80
80°
United States Range
Robeson Chan.
Archer Fd
Hall Land
Nansen Sound
Agassiz
Drill site
Meighen I
AXEL
HEIBERG
ISLAND
Greely Fiord
Eureka Sound
ELLESMERE ISLAND
Nares Strait
Kane Basin
Smith Sd
Inglefield Land
GREENLAND
Camp Century
Inglefield Bay
Olrik Fiord
78°
76
Hell Gate
BATHURST
ISLAND
Carey Is
Jones Sound
Coburg I
Baffin Bay
Devon
Drill site
DEVON ISLAND
0
100
200
Scale of Kilometers
Lancaster Sound
Bylot Island
96
88
80°
72°
64

FIGURE 1: *Location of drill-holes discussed in the text.*

(upward) one in the ablation zone. Accumulation is generally in the form of snowfall, whereas ablation is by melting and run-off from the ice cap. Accumulation predominates in the positive balance zone and ablation in the negative balance zone. In a steady-state ice cap, total accumulation equals total ablation in any one year. Its mass balance is then said to be zero. The important point for ice-core studies is that an accumulating snow-layer traps a variety of aerosols and gases with it. These aerosols and gases remain unchanged for many thousands of years.

RESULTS $\delta(^{18}O)$

Briefly, because (^{18}O) concentration in the snow is closely related to the temperature of condensation of that snow, a $\delta(^{18}O)$ time-series serves as a proxy temperature record. To substantiate this we present an empirical relationship between our δ values and recorded temperature data on the nearby West Greenland coast (Figure 2). All the records have been smoothed by a band-pass filter and show the close similarity between direct temperature records and a proxy (δ) one. We would not expect such a good relationship over time-scales of many millenia because of complications introduced by other variables. But for decades and centuries, we feel we can talk about δ values directly in terms of temperature.

It has been found that a change of 0.6 δ units in our cores is equal to 1.0°C change in temperature (Koerner and Russell 1979). Thus, the approximately 0.8 °/oo δ cooling between the 1930s and 1940s and the early 1970s on the Devon Island Ice Cap (DIIC) is approximately 1.0°C.

Godthaab, Greenland shows a similar temperature change. All these profiles are in general agreement with both a composite temperature profile for the northern hemisphere (0 - 80°N) and a profile for the last 60-70 years for southern Canada (Thomas 1975). If the ice cap record bears such close resemblance to that for west Greenland, and to that for southern Canada, then we feel confidence in extrapolating DIIC records to areas beyond the confines of the ice cap, i.e. the channels of the Queen Elizabeth Islands.

In previous papers (Koerner and Fisher 1981; Paterson *et al.* 1977; Fisher and Koerner 1981), we have presented $\delta(^{18}O)$ records from D72 and D73 that indicated pronounced cooling over the past 5,000 years, reaching its zenith in the Little Ice Age some 200 years ago. Here we will concentrate on the past 1,000 years of the D72, 73 and A77

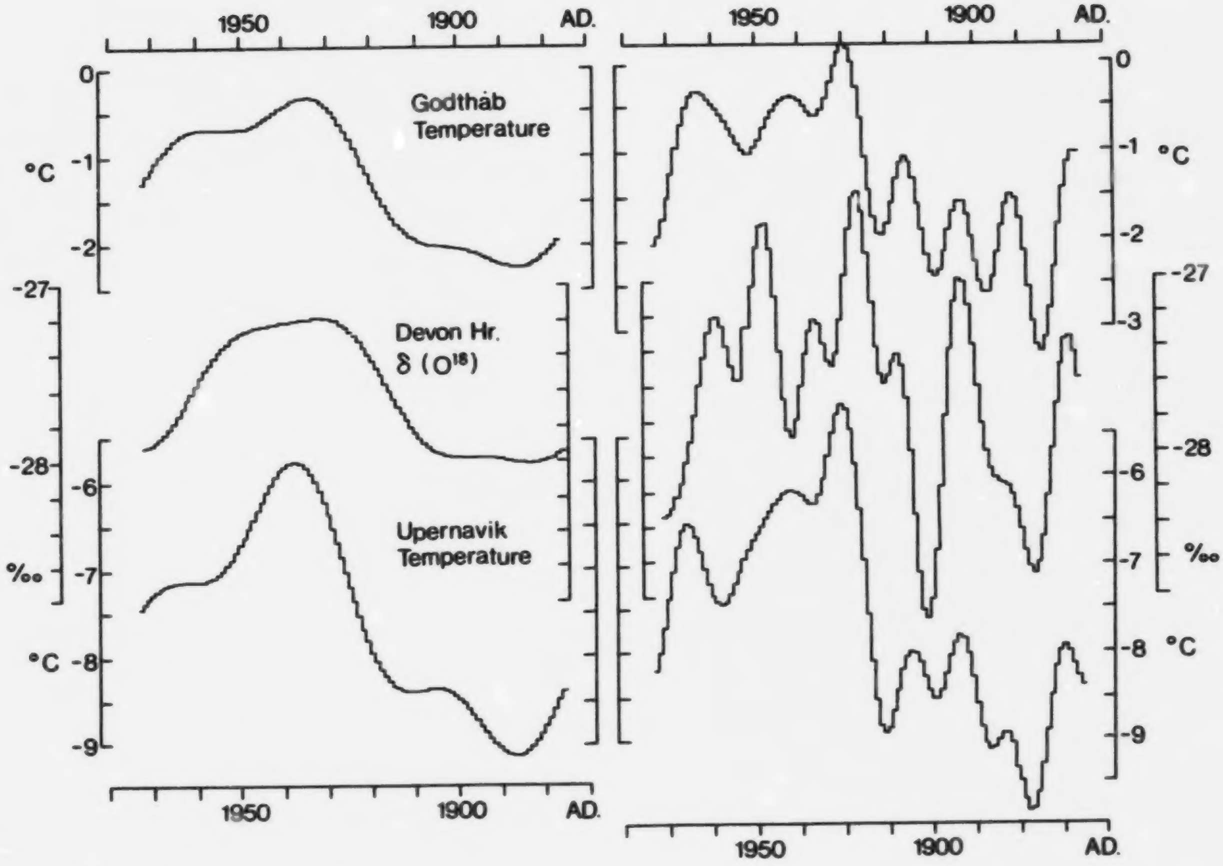

FIGURE 2: *Recorded temperatures (approximately 1875-1975) from the west coast of Greenland (Upernavik and Godthaab), and* $\delta(^{18}O)$ *values from the Devon Island Ice Cap (1800 m a.s.l.). Left-hand side smoothed with a 30 y low-pass filter and right-hand side with a 10 y filter.*

cores. Figure 3 shows a composite of our three main δ records. The δ Devon record is a blended one from two cores drilled 30 m apart. The overall δ trends between the areas are similar. The Little Ice Age is evident between approximately 1600 and 1800, and is followed by the warm period that reached its peak between the early and mid-twentieth century.

We draw attention to the Little Ice Age and the recent warm period because, isotopically speaking, we are juxtaposing the coldest period for the past several millenia and the warmest for the past several centuries. It presents itself as a substantial warming trend. However, it seems common practice to extract the latter part of this trend - say the past 100 years - and consider it in terms of anthropogenic (human) effects on the atmosphere. For example, Etkins and Epstein (1982) have attributed a recent (1890-1980) rise in sea level to a temperature rise of 0.4°C, half of which (0.2°C) went into melting Antarctic ice. They claim the warming is CO_2-induced and has been dampened by energy used to melt Antarctic ice. Our profiles show, however, that such warming is a continuation of one that began in the late eighteenth century - long before CO_2 began its dramatic increase in the atmosphere. It illustrates the dangers of taking one part of a cycle and discussing it out of context. We will discuss later the problems of relating "natural fluctuations" and anthropogenically-induced trends.

Data in Figure 3 also show the extent to which the annual temperature $\delta(^{18}O)$ can vary over a period of several hundreds of years. There is no period where one can truly refer to a "steady state" climate in terms of annual temperature. An early (1200-1300 A.D.) warm peak declines to an early cold period at about 1400 A.D., warming slightly before completing its decline to the Little Ice Age minimum about 1700 A.D. We then have the warming to which we have previously referred. The overall range on northern Ellesmere Island is from about -32 °/oo nearly 200 years ago to -30.5 °/oo two decades ago. On Devon Island, it is from -28.7 °/oo to -27.3 °/oo. In each case a range of about 1.5 °/oo represents a temperature change of 2.5°C. This figure is important because it acts as a natural variability standard with which to compare future possible anthropogenic effects.

Before considering the implications of such a degree of temperature variability, we will succumb to the irresistible temptation of projecting this record forward to obtain an estimate of what we might expect in the next 50 years.

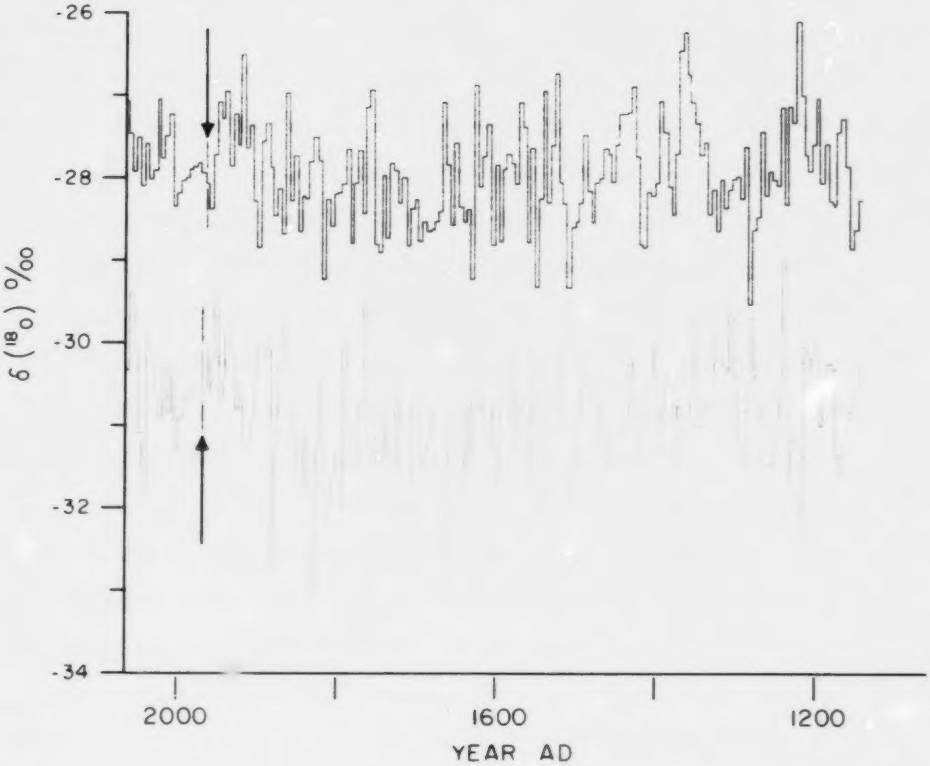

FIGURE 3: *δ¹⁸O record and prediction for Agassiz Ice Cap, northern Ellesmere Island (lower profile), and Devon Island Ice Cap (upper profile). 0.6 ‰ represents a temperature change of 1°C. Arrows separate the actual δ record to the right from the prediction to the left.*

PROXY TEMPERATURE EXTRAPOLATIONS

Long-time series can be extrapolated some fraction of their length - the more periodic the series, the longer and more valid the extrapolation possible. For example, the variation of insolation caused by changes in the earth's orbital elements can be reliably extended far into the future (Vernekar 1977). If there are real periodicities in the time-series that have a constant period, amplitude and phase, then the extrapolation procedures described produce very "accurate" results. Even series consisting of random data (pure noise) can be extrapolated a short distance beyond each end of the series. The data sets discussed here are a mixture of a quasi-periodic component and noise. The variance of both noise and signal in the ice core series is concentrated in the lower frequencies (long periods). This means that the variables change rather slowly with periods of proxy warmth or cold, lasting many decades before changing.

Extrapolated values can be calculated either by a spectral synthesis or an autoregressive prediction filter method. Both techniques have been tried, and give equivalent results. The first procedure involves deriving major periodicities in the data and adding them together in the correct phase relationship. Extrapolated values are then calculated using this sum or synthesis. In practice, the major variations in the ice core time-series can be reproduced by adding 2-4 sine waves of different periods, amplitude and phase. For example, variations of period 180 and 78 years added together account for 45% of the standard deviation of the Camp Century 10-year average δ record over the last 800 years (Dansgaard *et al.* 1971).

The second procedure represents a given value by a weighted sum of the past values, i.e. an autoregressive linear filter (Box and Jenkins 1976). Again, extrapolated values are simply calculated by using the weights found from the known data series. Extrapolation assumes that the "statistical nature" of the past proxy record will continue into the future. Man-made changes in climate could negate this assumption so that the extrapolations are of a "natural climate".

Instrumental records from the last 100-200 years do not lend themselves to extrapolation techniques of the kind we have used. Notable exceptions are the constancy of the 20-year cycle in North American winter temperature records (Mock and Hibler 1976) and midwestern

United States drought indicators (Roberts and Olsen 1975). Part of the reason for the general failure of the procedure to predict climate from instrumental records could be the length of the time-series available. From the ice-core series, for example, the periods most important for extrapolation are 80 years or larger. To obtain such periodicities one needs records longer than 400 years.

Even with the adequate length of the proxy series from ice cores, there may remain a healthy skepticism about the results of statistical extrapolation. Skeptics can still use the proxy records, however, to assess the variability of climate over long periods.

Using the proxy series as a source for predicting extremes is probably more useful for planning. Engineers and planners usually design for the extremes expected over some specified interval of time, i.e. the 50-year flood, the 100-year wave or the 30-year winter. Today's planners understandably tend to judge extremes from the instrumental record of this century. However, as pointed out here (see also Figure 4 and 5), this century has been an episode of extreme warmth, when viewed over the last millennium. Similar periods of warmth over the last 1,000 years have lasted 60-80 years. Therefore, the present one might well be expected to end and the climate cool towards a more commonly occurring level. If designers want to play safe and design for say the 400-year extremes, they should design for colder conditions than this century's records would lead them to expect.

Figure 3 indicates a continuation of the present cooling trend to at least 1990 and perhaps beyond. We stress that because of errors generated in the extrapolation methods only the general trend of this line is significant - individual five-year bars are not. It does not project a period of warmth comparable to the 1930s, 1940s and 1950s. The cooling is of the order of 0.5°C to 1.0°C.

This extrapolation agrees with another based on the Camp Century (Greenland) core, where there is "a more than 85% probability that the δ (temperature) curve will keep on the cold side of the -29 °/oo line in the next 10-20 years" (Dansgaard *et al.* 1971). In this case the -29 °/oo line is the 1,200-year average, and the δ record ends in 1967.

We will consider the effects on the High Arctic of such a cooling, after looking first at seasonal temperature variation and then the contribution of anthropogenic pollution to future climate.

SUMMER TEMPERATURE RECORD MELT FEATURES (FIGURE 4)

Each year in the High Arctic, increased energy income in summer melts most of the snow that accumulates over the previous winter months. Melting generally begins in late May/early June at sea level, and begins progressively later with increasing elevation. In most summers all the snow is removed from sea level to elevations of about 1500 m asl. Above this altitude, some melting generally occurs. This melting refreezes within the snow pack either as ice layers or in a more general form to produce hard, dense firn. Ice layers from refrozen meltwater can be recognized in ice cores down to a depth of about 150 m - representing about 1,000 years of accumulating snowfall.

We have successfully related the percentage of ice in each annual layer to both the mass balance of the ice cap and the maximum monthly amount of open water occurring each year in the channels between the Queen Elizabeth Islands (Koerner 1977). Thus our melt records may be reviewed (with caution) as proxy summer temperature and proxy sea-ice records. The results are shown in Figure 4.

While there are some clear similarities between the δ and melt records (cf. Figures 3 and 4), there are some interesting differences. Whereas, in terms of δ, the warm period this century is not unique (compare the 1300 warm spell), the melt-record suggests that, in terms of summer warmth, this century has experienced the warmest period in approximately the last 1,000 years. Both the Devon Island and Agassiz records show this. Herron *et al.* (1981) found melting between 1960 and 1979 was 1.4 times higher than the 2,200 years average in a core from West Greenland.

In many socio-economic situations, changes of summer climate have a much more profound impact than changes over any other season. This is true of the High Arctic where, for example, openness of the sea-channels in summer is taken advantage of to re-supply the various settlements and to take out raw materials excavated over the rest of the year. The warmth of the twentieth century coincided with the opening up of the North for both research and economic development. This coincidence has had a psychological effect of forming an erroneous impression of climate. Such an impression could have unfortunate consequences if it affects planning in the future. Consequently, to correct this impression, we have calculated a 50-year extrapolation of summer conditions using the same techniques as with

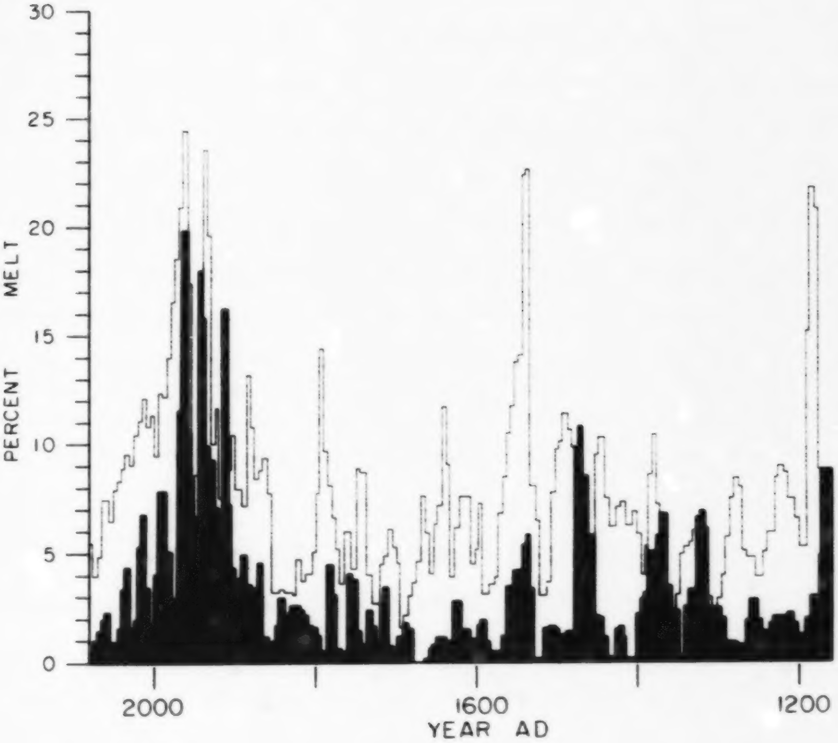

FIGURE 4: *Melt layers represented as the percentage of each annual layer of accumulation that has undergone melt to form an ice layer. The profile (white) for Devon Island Ice Cap (upper core) consists of a record to 1972 and prediction after that. For Agassiz Ice Cap, northern Ellesmere Island (black profile), the record/prediction dividing year is 1977.*

our δ values. The extrapolations from both the Devon Island and Agassiz cores agree (Figure 4) and suggest a continuing cooling and decline from the pre-1963 warm period.

Hibler and Langway (1977) made a similar forecast from ice-melt features in a core from the southern part of the Greenland Ice Cap: "The melt feature prediction suggests decreased melt occurrence until 2000 A.D.".

While extrapolations of this nature may be distasteful to some climatologists, overall agreement between six data sets (δ and melt in Arctic Canada and Greenland) is persuasive. We, therefore, do not expect the open summer sea-ice conditions of the 1920s to early 1960s to occur again in next 50 years. It is much more likely for more severe conditions than we have today to occur. What degree of severity it is difficult to say, but while we should expect annual temperatures to be 0.5 - 1.0°C colder, the tight sea-ice conditions of the 1972 summer (Table 2) will be more common, and may be surpassed in terms of ice concentration.

TABLE 2: *OPEN WATER AROUND THE QUEEN ELIZABETH ISLANDS AND MASS BALANCE AND ICE LAYERING (THICKNESS OF FEATURES BETWEEN 1600 AND 1800 m ABOVE SEA LEVEL) ON THE DEVON ISLAND ICE CAP.*

YEAR	PERCENTAGE OF TOTAL OPEN WATER	THICKNESS OF ICE FEATURES (mm)	MASS BALANCE (kg M^{-2} $year^{-1}$)
1961	58.6	55.0	-197
1962	69.8	80.0	-359
1963	52.7	4.4	+ 44
1964	33.9	9.8	+125
1965	35.3	0.8	+ 64
1966	46.2	54.0	-135
1967	-	20.0	+ 25
1968	34.9	0.0	+ 5
1969	41.3	92.0	-332
1970	36.7	16.0	+ 39
1971	50.4	49.0	- 69
1972	21.2	0.3	+102
1973	56.5	61.0	- 95
1974	40.5	33.0	- 77

There seems to be a lag of summer changes behind the annual temperatures (i.e. δ) changes in our core. Thus, the δ peaks were in the late 1920s and 1940s, whereas the melt peaks were in the 1930s and 1950s. There are examples of this lag correlation elsewhere in the 600-year records. It means that the full-cooling trend of the summers has not been felt yet.

If we look at what is happening on the ice caps (Figure 5), we get an inkling of the summer cooling effect. Ice caps in the High Arctic depend for their nourishment on snow that falls throughout the year. However, as so often happens in life, what is given with one hand is taken away with the other. So, a large part of that snow melts away in summer, along with some of the ice at lower elevations. The balance between snow that is left on the upper reaches of an ice cap and the ice and snow melted from its lower parts determine the ice bodies' health. The present situation on most ice caps of the High Arctic is that the amount of melt is the main determinant of its final state of health rather than the amount of snow that falls each year.

Looking at our records of the state of health (mass balance) of our High Arctic ice caps (Figure 5), we see the warm condition (i.e. negative balance due to mass loss) in the early 1960s which formed the end of the 30 to 40 year-long warm peak period referred to earlier. Since then, there has been a decreasing occurrence of very negative balances, that is warm summers (e.g. summers of 1971 and 1977 on Meighen Island; 1969 on Devon Island; and 1968 on Axel Heiberg Island). The only substantially-negative balance in the past decade has been 1971 on Meighen Island.

ANTHROPOGENIC EFFECTS

We are still in a position where we have to base our predictions on long-period records that do not include strong anthropogenic (man-made) effects, which only began to emerge in measurable amounts this century. It is impossible to accurately assess the effect of human pollution on climate from our data. Anthropogenic influences may be considered under three categories: (1) direct thermal input; (2) dust and gaseous pollution effects; and (3) carbon dioxide production with its greenhouse effect. We will briefly consider each of these.

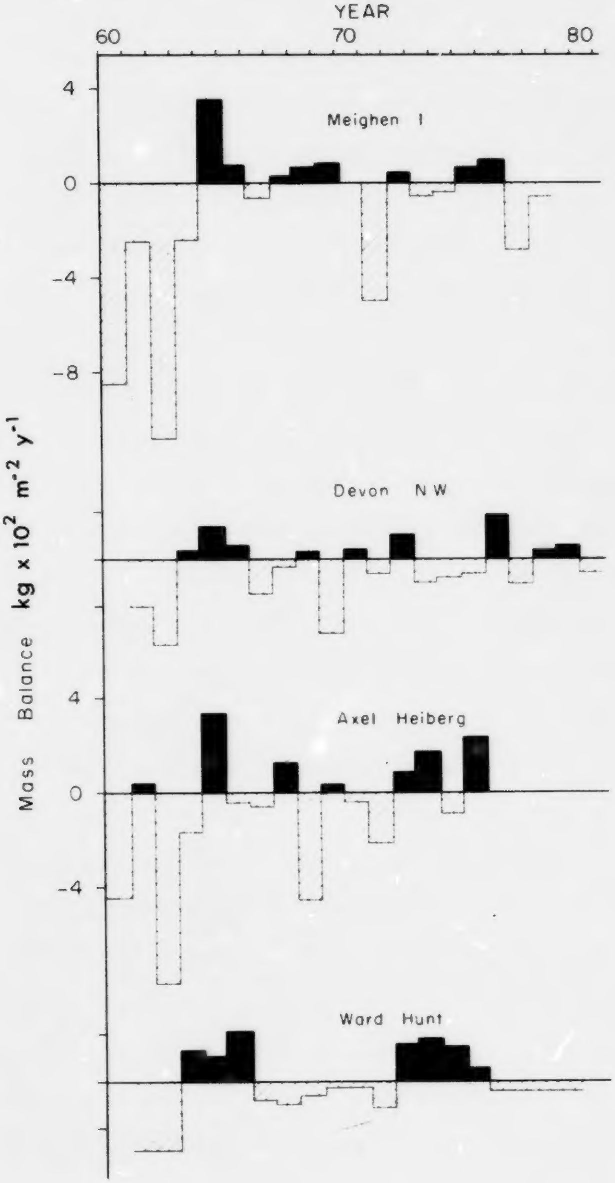

FIGURE 5: *Mass balance for four ice bodies in the Canadian High Arctic (1960-80). Data from Meighen Island are for a small ice cap, Devon Island for the northwest side of the main ice cap, Axel Heiberg for White Glacier (a small valley glacier) and Ward Hunt for a 1 km side grid of 100 stakes on the ice shelf of that name.*

(1) Thermal Input. Several assessments of the effect of direct heat input into the atmosphere have been made and are well summarized in Bach (1976). The consensus of opinion is that presently they are insignificant. However, it has been calculated that by the year 2000 anthropogenic heat input to the atmosphere may reach the 100-300 trillion watts level which, according to one authority (Flohn 1974), is sufficient to cause climatic change. Other authorities disagree, and thermal pollution does not figure very largely in most climatic Doomsday philosophies.

(2) Dust and Gaseous Pollution. The effect of dust on climate is hotly disputed. A reasonable overview concludes that increased dust in the stratosphere causes a cooling and increased dust in the troposphere, a warming (Bach 1976). One generally reliable authority (Mitchell 1975) concludes that by the year 2000 anthropogenic dust will, if anything, cause a slight warming.

What we find in our cores is intriguing. Over the past 10,000 years dust levels in the ice (and hence in the atmosphere above) have not changed significantly. We record several very dramatic volcanic effects, but at present find no strongly associated temperature change in the $\delta(^{18}O)$ record. In addition, general volcanic fallout, as measured by the acidity of the ice[1], shows no significant trend over the past 10,000 years, and individual events do not seem to have had a noticeable effect on the associated record. Thus, we conclude that the cooling trend we have in our 5,000-year record is not driven by dust variations or volcanic effects.

However, Hammer *et al.* (1980), from a study of acid layers in Greenland, feel that while individual volcanic events may not affect climate for more than a few years, the general change in the level of volcanic activity does. They relate the number of Greenland volcanic layers (acidity) to the record, and finds an inverse volcanic/δ relationship, i.e. cooler temperatures with increasing volcanic activity.

(3) CO_2 Production. As this anthropogenic affect is dealt with at some length elsewhere in this volume by F.K. Hare, we will consider it only briefly. Currently, CO_2-warming (a

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[1] Gases ejected from a volcano and entering the stratosphere are converted to H_2SO_4, which is then removed by precipitation as acid rain or snow.

greenhouse effect) is generally regarded as the most serious of the various anthropogenic effects on climate. Originally, it was thought that the warming at the first half of the century was directly attributable to increasing CO_2 levels in the atmosphere. However, the warming trend has now changed to a cooling one. Furthermore, the warm period in the pre-1960s is predicted when we take the pre-1900 part of various proxy records and project it forward into this century. In other words, the warm period in the first half of this century probably has natural origins. We have already drawn attention to the fact that the warming trend begins *before* CO_2 levels began increasing in the atmosphere.

If we look at our mass balance records for the last 20 years, we see no direct evidence of the effect of increased levels of CO_2. Ice-core data (Figures 4 and 5) confirm this. Oceanic thermal inertia and/or a natural cooling cycle (as for example the one we and others predict) may be compensating for, or masking, a CO_2 effect, if indeed there is one. However, predictions are that the CO_2 effect will be apparent only around the turn of the century with a "high probability" or some warming in the 1980s. The polar regions are expected to warm the most and, ignoring the more dramatic Doomsday forecast, we would draw attention to one favourable conclusion which is the opening of the Northwest Passage (Madden and Ramanathan 1980).

But we must still be careful of any CO_2-related predictions, because empirical studies (Newell and Dopplick 1979; Idso 1981) suggest that climate models overestimate the radiation effect by a factor of 10. This would mean the CO_2 effect is similarly exaggerated. These studies serve to show that much is still to be done before we gain an adequate understanding of the atmosphere-energy relationship.

Here, ice-core studies may be able to contribute. By studying the CO_2 fraction in air bubbles of cores, it has already been found that CO_2 levels in the atmosphere during the last ice age (approximately 60,000 to 10,000 years ago) were one half of today's levels (Delmas *et al.* 1980). At present it remains a chicken and egg problem. Was climatic change causing lower CO_2 levels, or were lower CO_2 levels causing the climatic change? It is difficult to envisage a reason for the very sudden increase in CO_2 10,000 or more years ago unless it was caused by changing climate. In this case, the warming proceeded regardless of quite low CO_2 levels in the atmosphere. Perhaps because of CO_2 released from the warmer oceans, the CO_2 concentration in the atmosphere increased to nineteenth century levels as a result of the warming. Possibly, careful CO_2 measurements in Holocene ice (0-10,000 years ago) may be compared to δ values in the same ice to gain some understanding of the CO_2/air temperature relationship.

CLIMATIC CHANGE AND ITS EFFECTS IN THE HIGH ARCTIC ENVIRONMENT

Climatic change has had a profound effect on historic Inuit settlement and activity in the High Arctic. This was documented in the first volume of this series (Harington 1980). The main effect of climatic change in terms of non-Inuit human activities in the North seems to us to be *via* a change in sea-ice conditions. In a 13-year record the maximum extent of open water in the Queen Elizabeth Island channels each summer (usually in September) has varied from 20% in 1972 to 70% in 1962 (Table 2). Over a period of centuries, we conclude from Figure 4 that the history of the quest for the Northwest Passage was tied to climatic change. The colder climate of the pre-twentieth century was probably the main reason the British were thwarted in their attempts to achieve, or even discover, the Northwest Passage through the Islands, rather than inappropriate methods. It was left to first Amundsen and then Larsen in the warmer early- and mid-twentieth century, with its more open ice conditions, to make their successful voyages.

More recently (1969), the SS Manhattan, with the assistance of an icebreaker, forced a route through the Northwest Passage. That year, we find from sea-ice (Lindsay, in press) and Devon Island Ice Cap mass-balance records that the summer was warmer than usual in at least Lancaster Sound, where there were larger areas of open water than usual. The passage would have been much more difficult, perhaps unsuccessful, if undertaken in 1972.

A cooling trend, especially in summer conditions in the next 50 years, would be accompanied by fewer open sea-ice conditions during summer. As the Arctic Ocean may be similarly affected, there could also be a larger and more consistent invasion of the Queen Elizabeth Island channels with multi-year ice. Closer Arctic pack conditions and stronger (multi-year) ice within it mean that shipping plying these channels must be strength-designed on the basis of such expectations. The design of LNG (Liquid Natural Gas) tankers is especially pertinent here.

CONCLUSIONS

Ice cores provide valuable proxy climatic records. They can be used to measure the degree of variability of climate in the past and place present climate in its true perspective. Ice cores do not incorporate a long enough record of anthropogenic effects to allow presentation of a combined natural/anthropogenic prediction of climate. However, extrapolations of proxy temperature records should be considered in the formulation of any models of anthropogenic effects on climate. Climate-modelling cannot be based on the assumption of a flat natural background as climate is, and has always been, a continuously-changing phenomenon. Global climate models may predict a warming over the next 100 years, because of the effect of increasing concentrations of CO_2 in the atmosphere. However, this warming should be incorporated with extrapolations of proxy temperature records to better estimate a realistic climatic change.

An important Canadian contribution to climatic change lies in monitoring the changes as they take place. The High Arctic ice caps provide an ideal climate integrator, and we plan to measure the mass balance of some of these ice caps each year and to publish the records regularly in order to extend the present 20-year record. As far as we are aware, these records represent the longest and most continuous series of mass balance measurements taken at such high latitudes.

As our proxy temperature extrapolation is no more than a best estimate of a natural climate change, our ice cap mass balance measurements may serve to test this prediction and perhaps separate out any anthropogenic effects on High Arctic climate.

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SYNOPTIC ANALOGS: A TECHNIQUE FOR STUDYING CLIMATIC CHANGE IN THE CANADIAN HIGH ARCTIC

Bea Taylor Alt[1]

INTRODUCTION

Considerable emphasis has been placed, recently, on the study of climatic change through analysis of trends in temperature on both hemispheric (Kukla *et al.* 1977; Angell and Korshover 1977: Harley 1978; and others) and regional (Bradley 1973A, 1973B; Bradley and England 1979; Kirch 1966; and others) scales. In the Queen Elizabeth Islands (QEI, Figure 1) mass balance measurements are available beginning in 1960, whereas meteorological records begin in the late 1940s. This brief period of record provides only a glimpse of the climate of the QEI and allows discussion of only short-term trends. Even on a hemispheric scale Kukla *et al.* (1977) note, "The range of year-to-year variability in most data sets is several times larger than the departure due to long-term trends.". In the QEI where Maxwell (1981) indicates a 0.5°C decrease of temperature during the period of record, standard deviations of monthly mean temperature range from 1 to 4°C (P.R. Scholefield, personal communication, 1982). The impact of these year-to-year variations is magnified by the sensitivity of the Arctic environment to small changes in temperature-particularly during spring and summer. These season-to-season variabilities can, however, be exploited as a means of examining the degree to which paleoclimatic changes, of the order of magnitude of the Climatic Optimum and Little Ice Age, can be accounted for by changes in the frequency of occurrence of present synoptic weather patterns.

METHODOLOGY

The ultimate goal of climatic change studies must be an understanding of the mechanisms linking geophysical and ecological processes with the general circulation of the atmosphere. On one hand, such an understanding would allow assessment of the impact of a change in

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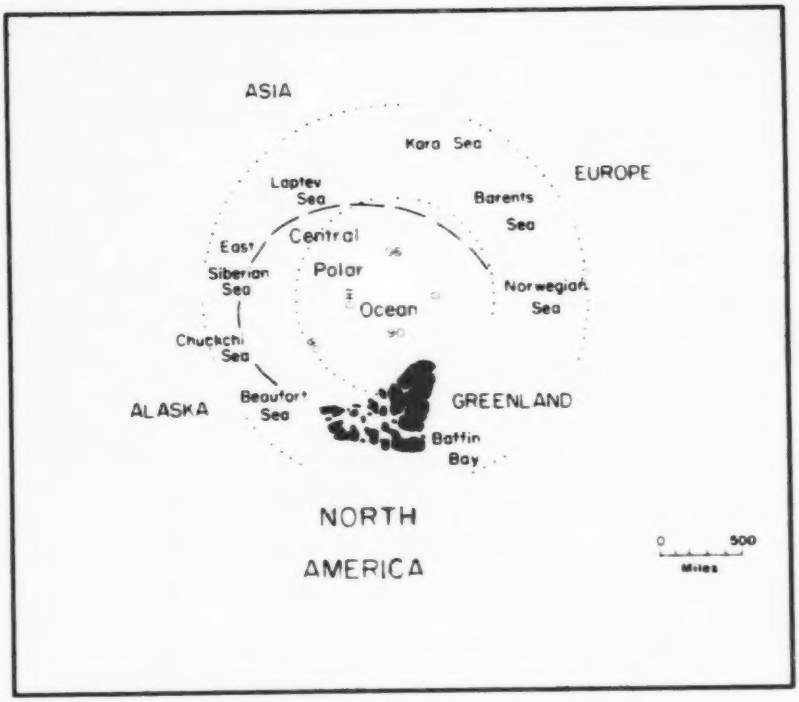
ASIA
Kara Sea
EUROPE
Laptev Sea
Barents Sea
Central
Polar
Ocean
East
Siberian Sea
Norwegian Sea
Chuckchi Sea
Beaufort Sea
ALASKA
GREENLAND
Baffin Bay
NORTH
AMERICA
0
500
Miles

FIGURE 1A: *Map of the Arctic Basin showing Central Polar Ocean (polar pack ice) and peripheral seas (summer break-up). The Queen Elizabeth Islands (QEI) are shaded. Sectors referred to in the text are labelled.*

atmospheric circulation, while on the other, it would allow use of evidence from climate-related processes to reconstruct past circulation patterns. This goal is presently well beyond our reach. Many researchers are pursuing the problem, each from their own perspective. My perspective originated in the need to explain the existence of Meighen Ice Cap (Alt 1975). In the process, a simple subjective synoptic classification system was developed for the summer months based on six summers of data from Meighen Ice Cap. The classification scheme was kept simple to allow its use in paleoclimatic discussions. It was necessary to understand the interaction of melt (produced by surplus energy at the ice surface) and accumulation (resulting from solid precipitation) with weather conditions near the surface and in the upper atmosphere. Numerical classification systems (e.g. Kirchoffer 1973; Lund 1963; Bradley and England 1979) require use of one parameter at one level in the atmosphere (usually the surface) and thus, for the initial phase of the study, were not suitable. Subjective techniques allow examination of surface and upper air synoptics and their effect on various climate, energy balance, and mass balance parameters.

The mass balance of an ice body is the net gain (positive) or loss (negative) of snow, firn or ice in a season. The mass balance season, used in the following discussions, begins after the final melt event of summer and is broken into the winter accumulation season (which is misleading as most accumulation occurs in fall and spring) and melt season or summer (which extends from first to last melt event). On High Arctic ice caps the melt season, thus defined, may include periods of below-freezing temperatures and solid precipitation. The net balance values are more variable and correlate better with annual mass balance values than do winter accumulation amounts, which are normally in the 15 - 20 cm/yr range on Meighen Ice Cap. Emphasis is thus placed on summer synoptic patterns in mass-balance studies. In specific years (such as 1964), winter accumulation anomalies significantly affect mass balance, while in other years (such as 1962 and 1972) the circulation characteristics of the preceding winter and spring increase the intensity of summer temperature anomalies.

The Meighen Ice Cap synoptic classification was developed from examination of data listed in Table 1A. The frequency of occurrence of the resulting circulation types was successfully related to seasonal mass balance for the period 1960-73 (Alt 1979). A similar study (Alt 1978) was undertaken for Devon Island Ice Cap based on the energy-balance studies of Holmgren (1971).

Examination of climate change on a paleoclimatic scale requires that daily synoptic classifications be translated into seasonal and decadal circulation patterns. Pursuant to this, a detailed study was undertaken of seasons experiencing extreme mass balance and climate conditions throughout the QEI. The information incorporated in the study is listed in Table 1B, and the geographical locations are shown in Figures 1A,B.[1]

Before presenting the results of these studies, a few words are necessary on the significance of the 500 mb-level and its use in the classification system. Due to the earth's rotation and the temperature gradient between high and low latitudes, the middle and upper atmosphere in the north polar region is dominated by a cold core circumpolar vortex. This vortex extends from about 2 km up to 15-20 km, and is thus well defined on the 500 mb-charts (5.5 km)[2]. The 500 mb-level occurs near the middle of the troposphere, well above the influence of surface synoptic features and well below the tropopause as illustrated by the 10-day temperature soundings from Isachsen (Figure 2A). As average sea level pressure is 1013 mb, roughly half of the mass of the atmosphere lies below 500 mb and half above. The equations of motion are simplified at this level as the horizontal divergence term can be dropped. For this reason, the 500 mb-level is important in operational forecast models as well as in general circulation models. The synoptic features at the earth's surface are very shallow and considerably more complex and changeable than the 500 mb-pattern. The lack of data over the Polar Ocean precludes accurate definition of the surface pattern to the north and west of the QEI, a problem which is less severe at 500 mb due to the relative simplicity of the pattern.

The mean summer pattern of the 500 mb-vortex conforms to the shape of the Arctic Basin (Figure 2B). We would expect areas within the Arctic Basin, which includes the QEI, to be uniquely dependent on the behaviour of the polar vortex. It is not surprising, therefore, that as study of the synoptics of the region progressed (Alt 1978, 1979), increasing emphasis was placed on the 500 mb-pattern. It became the key to defining the basic circulation patterns which produce extremes of climate and mass balance in the QEI. Through-

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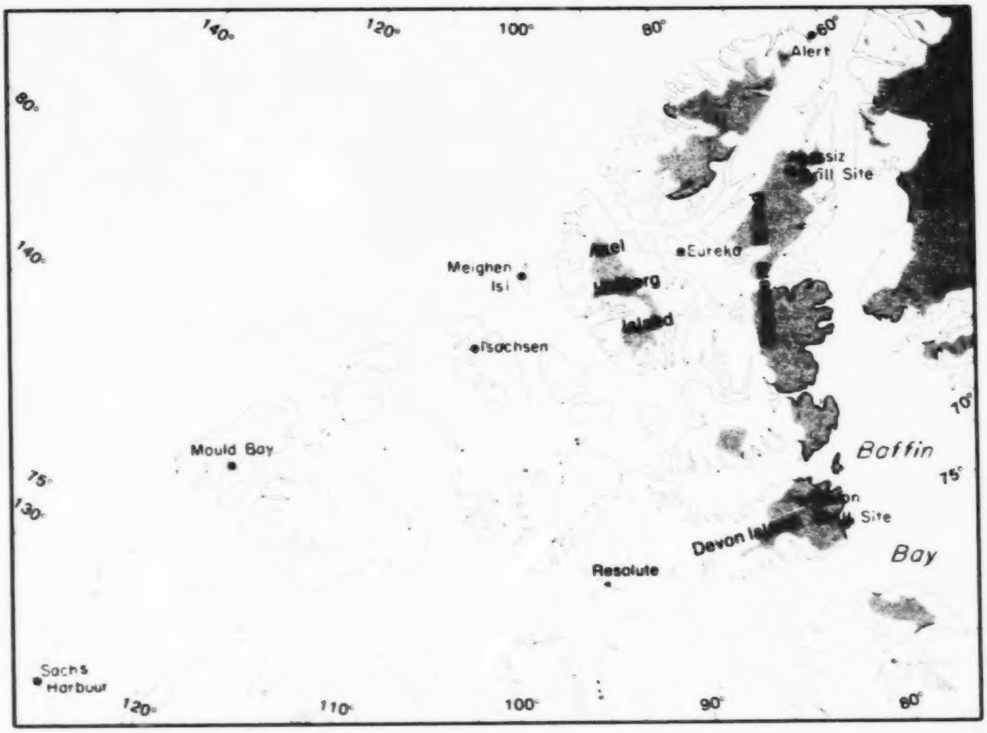
[1] Note that the term "Central Polar Ocean" (Orvig 1970) is used to define the region of the Arctic Ocean poleward of the peripheral seas. Throughout this paper it is referred to as "Polar Ocean".

[2] Synoptic charts are available for the surface (pressure, mb) and the 850 mb (ca. 1.5 km), 700 mb (ca. 3 km) 500 mb (ca. 5.5 km) and 300 mb (ca. 9 km) levels (height contours of constant pressure surfaces).

TABLE 1: ***INFORMATION AND SOURCES USED IN DEVELOPING THE SYNOPTIC CLASSIFICATION FOR MEIGHEN ICE CAP AND EXTENDED HERE TO THE OTHER QUEEN ELIZABETH ISLANDS (QEI).***

PERIOD	DATA USED	SOURCES
A		
Hourly values, daily means, 10-day means and wind roses.	Climate parameters: field stations Meighen Island six summers (June, July, August).	K.C. Arnold (1960, 1961, 1962). B. Alt (1968, 1969, 1970).
Hourly values, daily means, 10-day means and wind roses.	Energy balance components measured in 1968, 1969, 1970 and calculated for six seasons using ERBA computer program.	B. Alt (1975).
	Synoptic Energy Balance Diagram.	B. Alt (1975).
Daily values.	Surface lowering, six seasons.	K.C. Arnold, B. Alt.
Seasonal values.	Mass balance.	K.C. Arnold, W.S.B. Paterson.
Hourly values, daily means, 10-day means and wind roses.	Surface data: 1960-74. Upper air data: six seasons. Isachsen and Eureka.	Atmospheric Environment Service (computer cards 1, 4 and 5).
00 and 12GMT daily.	Surface, 850 mb, and 500 mb-Canadian Meteorological Centre synoptic charts (1960-78).	Atmospheric Environment Service (on microfilm).
B		
Daily and monthly means, 1941-70 normals and anomalies.	Temperature, precipitation and other climate parameters for five stations, plus Sachs Harbour and Clyde.	Atmospheric Environment Service Monthly Record calculated by B. Alt and P.B. Scholefield (personal communication).
Monthly means and anomalies.	Regional averages: Keewatin, Franklin E., Franklin W. and Inuvik - Tuktoyaktuk.	Calculated from Atmospheric Environment Service Monthly Record.
Seasonal values, daily values.	Mass balance, accumulation, melt and equilibrium line attitude (ELA) for QEI glaciers.	Koerner (in preparation), Holmgren (1971), Keeler (1964).
Monthly means.	July 500 mb-height patterns.	T. Jacobson (personal communication).
Daily.	Position of main 500 mb-vortices relative to QEI.	Extracted from 500 mb-GMT charts.



140°
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100°
80°
60°
Alert
80°
ssiz
ill Site
140°
Meighen
Isl
Eureka
Isachsen
10°
Baffin
Mould Bay
75°
130°
15°
Site
Devon Isl
Bay
Resolute
Sachs
Harbour
120°
110°
100°
90°
80°

FIGURE 1B: *Map of the QEI showing weather stations, drill sites, and extent of glacier ice. (Clyde is located off the southeast corner of the map about half way down the east coast of Baffin Island. Isachsen is no longer a weather station).*

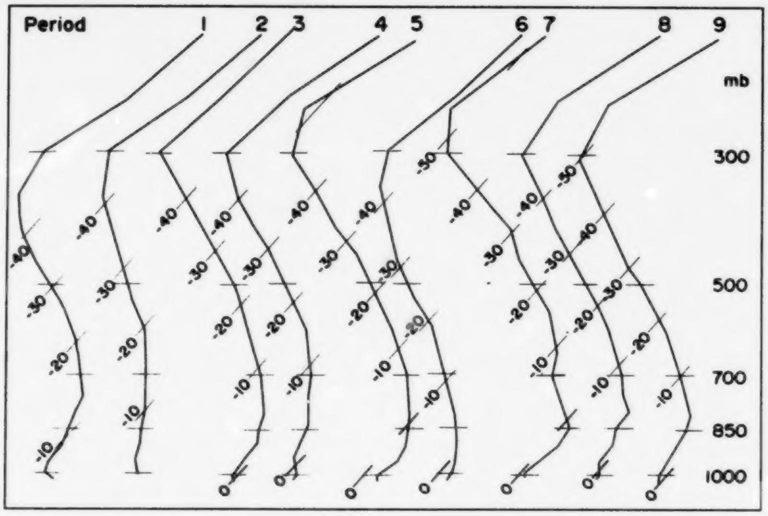

FIGURE 2A: *Ten-day means of upper air temperature 1970 (^{o}C) for Isachsen plotted on a Tephigram (thermodynamic diagram used as a forecast tool). Note that lower atmospheric features can extend beyond the 700 mb-level and that the tropopause can occur at or below the 300 mb-level.*

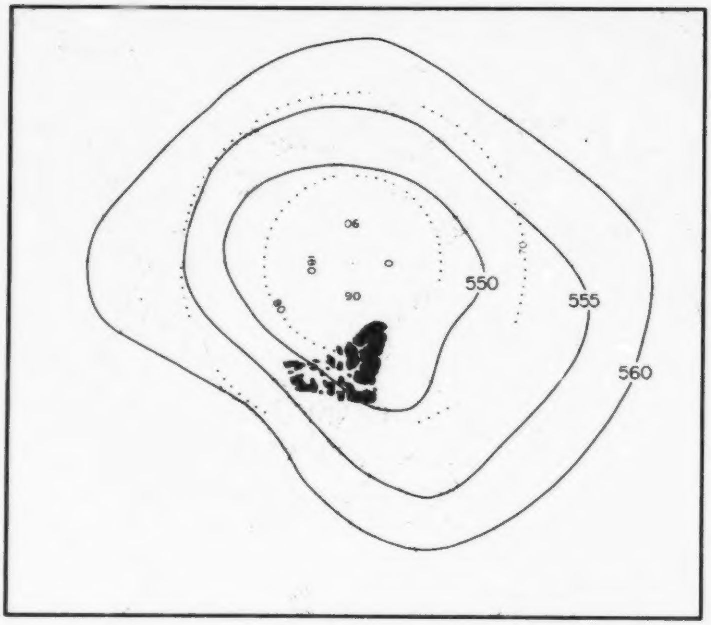

FIGURE 2B: *Mean July pattern of 500 mb-height contours (dam) for 1948-1978. In order to focus on the polar vortex only contours up to 560 dam are shown.*

out this paper synoptic discussion will refer to the 500 mb-level unless otherwise specified, and "vortex" always refers to an upper air feature visible on the 500 mb-charts.

As it was necessary to represent the domination of a particular type of circulation by a seasonal mean, 500 mb-charts for the months of July from 1949-1978 were examined. July was chosen as the month representing summer conditions, though in fact June and August can significantly affect the intensity and duration of melt-season events. Mean charts can be misleading or, at best, difficult to interpret if one is not cognizant of the individual events which produced that mean. To circumvent this, the positions of the 500 mb-polar vortex centres deemed important to the QEI (e.g. Figure 3D) were recorded for each day of June, July and August of the seasons studied.

SUMMARY OF SYNOPTIC STUDY RESULTS

Climate controls on glacier mass balance operate in three ways: through melt, melt suppression, and summer accumulation (augmented by increased winter accumulation). Each of these controls is represented in the following discussion by a season exhibiting a universally-strong influence of that control across the QEI. Figures 3, 4 and 5 illustrate the development of seasonal conditions from the dominance of specific synoptic situations, and are based on Alt (in preparation). The synoptic type nomenclature developed in previous studies is extended here to the whole QEI (Table 2). *"Type I"* refers to a specific synoptic occurrence while *"I"* refers to a season or decade dominated by *Type I* occurrences. The 1941-70 normals are used throughout the paper (for the QEI ca. 1949-70).

High Melt in the QEI (Represented by 1962):
No North American Sector Vortex at High Latitudes (III)

Highly negative mass balance conditions were experienced on all QEI glaciers in 1962. The average QEI summer season temperature for 1962 was 2°C above the 1961-77 mean. The summer of 1962 was dominated by blocking anticyclone conditions *(Type III* in the QEI associated with positioning of the vortex on the Eurasian side of the Arctic Basin (Figure 3A). These conditions appeared as early as the beginning of June. Positive temperature anomalies associated with anticyclonic dominance were strongest in the central

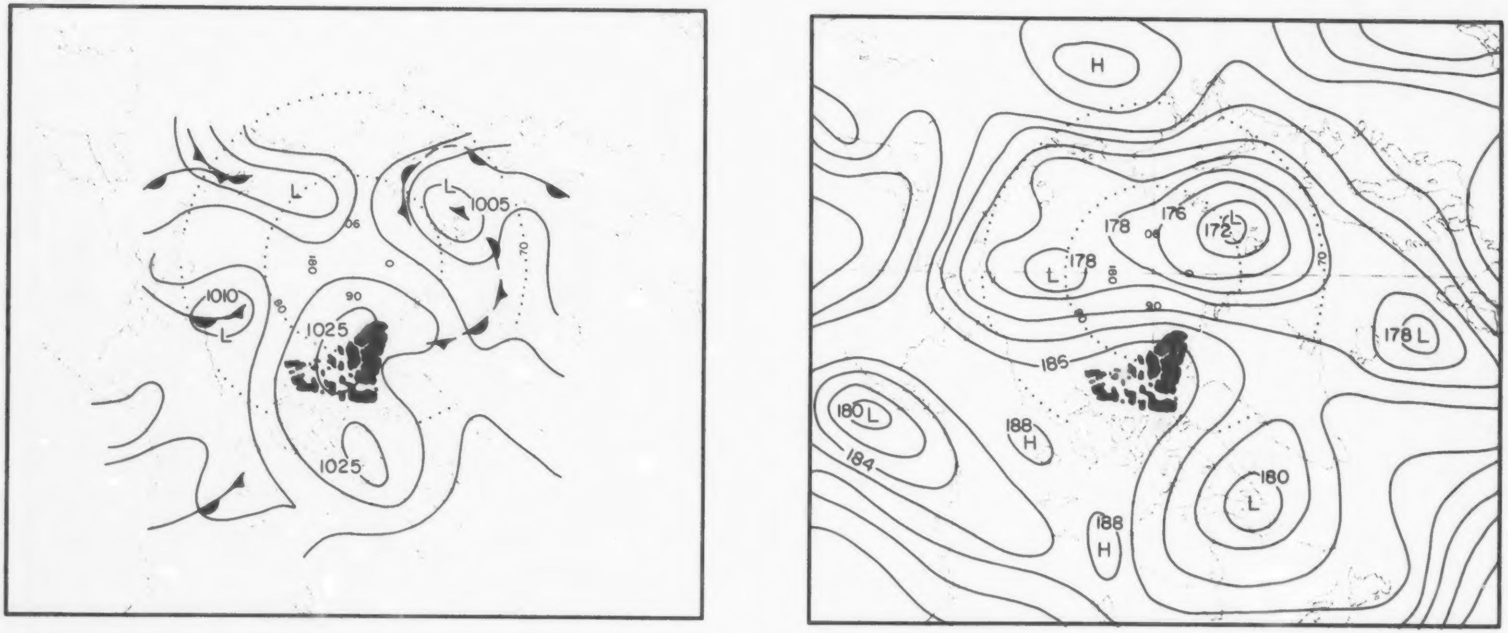
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FIGURE 3A: **TYPE III** - *Synoptic conditions for July 20, 1962. Surface pressures (left) in mb and 500 mb-height contours (right) in hundreds of feet. Melt maxima occurred in the northwest (Meighen I. and Axel Heiberg I.), and secondary maxima occurred at low elevations (Sverdrup Glacier on Devon I.). In the northwest subsidence which destroys the fog, warm air advection and solar radiation produce the melt. On outlet glaciers, due to low surface albedos, solar radiation is the controlling factor.*

TABLE 2: *SYNOPTIC-TYPE NOMENCLATURE DEVELOPED IN PREVIOUS STUDIES AND EXTENDED HERE TO THE OTHER QUEEN ELIZABETH ISLANDS (QEI). "TYPE I", ETC. REFERS TO A SPECIFIC SYNOPTIC OCCURRENCE, WHEREAS "I" REFERS TO A SEASON OR DECADE DOMINATED BY* TYPE I *OCCURRENCES.*

TYPE	SURFACE SYNOPTICS	500 MB-VORTEX
III	Anticyclone.	Ridge in QEI; Vortex in Eurasian sector.
IIr	Tracking cyclone with rain.	Vortex in Beaufort Sea sector.
IIs	Tracking cyclone with snow.	Vortex moving across Islands.
I	Baffin Low; Polar Ocean High.	Vortex in North American sector.

and northern portions of the QEI, where monthly mean temperatures up to 3°C above normal were experienced.

In late July of 1962 the vortex shifted to the Beaufort Sea sector (Figures 3B,C) and the warm sector of a surface frontal system penetrated the QEI *(Type IIr)*. Melt and temperatures peaked on Devon Island Ice Cap.

Anticyclonic conditions were re-established in early August. The North American sector vortex did not regain dominance until mid-August. The vortex centre position plot (Figure 3C) shows graphically the absence of the North American sector vortex throughout the melt season of 1962.

The mean 500 mb-pattern for 1962 (Figure 3D) shows a ridge through the QEI with the vortex shifted to the East Siberian Sea sector. However, the central height was similar to the 1949-78 mean (Figure 2B). In 1962, positive summer temperature anomalies were not experienced universally around the periphery of the Arctic Basin. In northern Scandinavia, mean July temperatures were below normal (World Meteorological Records), and mass balance on Norwegian and Swedish glaciers was positive (Kasser 1967). For these reasons 1957 was also examined. In that year, the QEI showed strong positive temperature anomalies and Dronia's hemispheric 100-500 mb thickness value is well above normal at high latitudes. The mean July 500 mb-pattern for 1957 (Figure 3E) shows a weakened vortex in the East Siberian Sea sector and weak circulation at high latitudes in the North American and Norwegian-Barents Sea sectors.

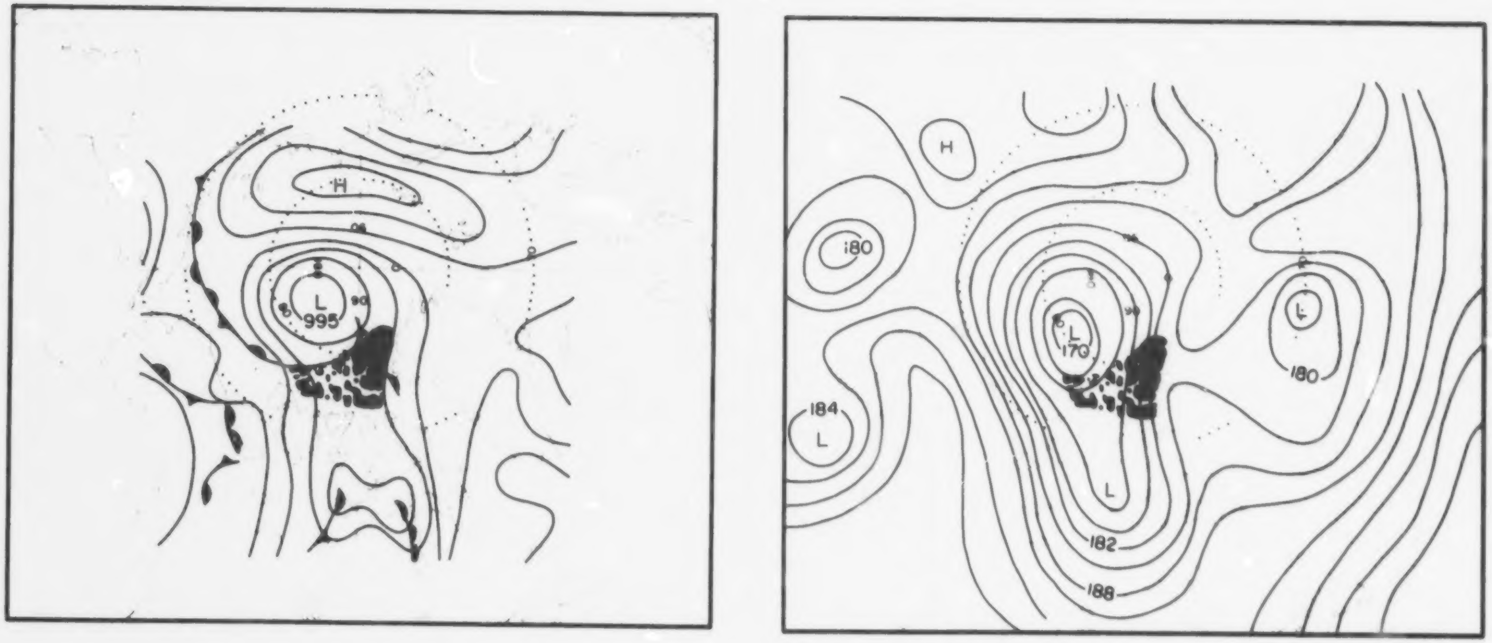

FIGURE 3B: **Type IIr** - *Synoptic conditions for July 30, 1962. Surface pressures (left) in mb and 500 mb-height contours (right) in hundreds of feet. Melt maxima occurred in the southeast (Devon Ice Cap), and increased in relative intensity with elevation. Temperatures peaked in southeast, but snow fell on Meighen Ice Cap. Warm air advection, strong winds, overcast skies and rain on Devon Ice Cap resulted in energy gain to the snow surface by latent and sensible heat fluxes, and decreased loss by long-wave radiation and lowering of the surface albedo.*

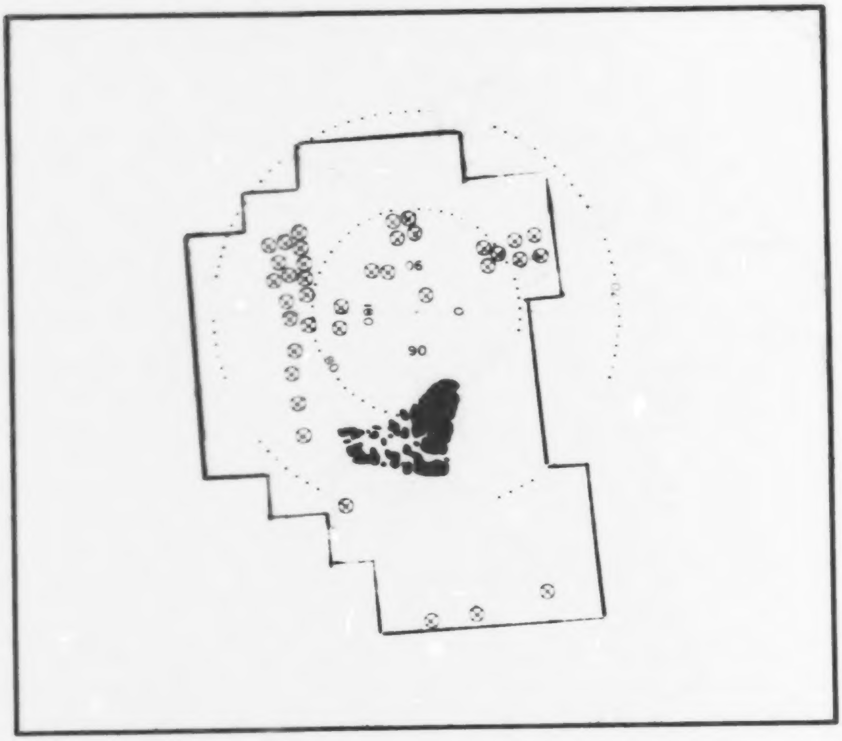

FIGURE 3C: *Position of main 500 mb-vortex centres over the Polar Basin for July 1 to August 10, 1962. This period represents the normal melt season on Devon Ice Cap. The main vortex (vortices) was identified on the basis of height and temperature contours, and position relative to the QEI. Low centres on land or outside the area indicated by the grid outline were not considered to directly influence the QEI. In some cases two vortices of equal strength and/or influence occurred simultaneously. In this case both were plotted.*

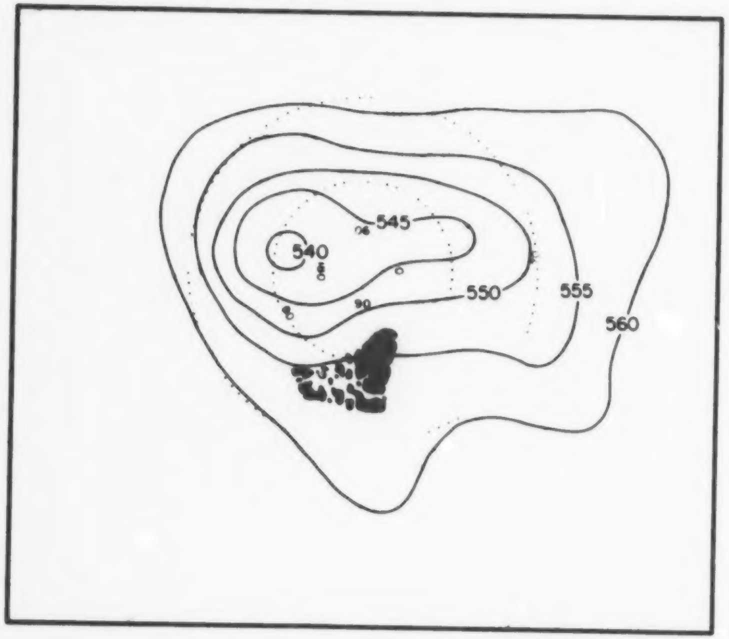
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FIGURE 3D: III - *July 500 mb-pattern for 1962. Height contours in dekameters (dam). In order to focus on the polar vortex only contours up to 560 dam are shown.*

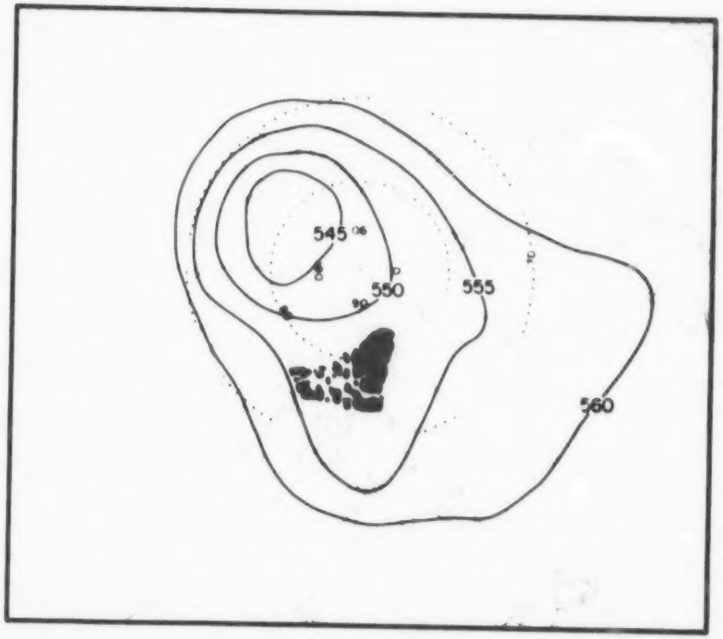
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FIGURE 3E: *July 500 mb-pattern for 1957. See* FIGURE 3D.

To summarize, universally-high melt across the QEI requires dominance of anticyclonic conditions (*Type III* occurring more than 40% of summer season) with at least one well-developed, warm frontal tracking cyclonic situation (*Type IIr*). The season of 1962 is used to obtain values of climate and glacier parameters for a *III* season (Table 3). The 500 mb-patterns of 1962 and 1957 (Figures 3D,E) can be combined to represent the mean July conditions of anticyclonic-dominated *III* seasons.

TABLE 3A: *CLIMATIC CHARACTERISTICS FOR THE QUEEN ELIZABETH ISLANDS (QEI) OF VARIOUS PERIODS SHOWN IN TABLE 3B.*

NAME	MASS BALANCE CHARACTERISTICS	SUMMER SYNOPTIC CHARACTERISTICS IN THE QEI	500 MB-PATTERN (FIGURE NO.)	YEARS OF DATA USED IN REPRESENTATION
III	HIGH MELT	Season dominated by anticyclonic circulation.	3 D, E	1962
III/IIr	*Hypothetical Decade Maximum Melt*		*6 A*	*III and IIr (5/5)*
50-yr	*Hypothetical 50-Yr Period Similar to the Most Recent 50 Yrs.*		*6 B*	*III/IIs and STUDY PERIOD (2/5)*
NORMAL	CLIMATOLOGICAL NORMALS 1941-70		2 B	1949-70
IIr	MODERATE MELT	Season(s) dominated by surface cyclonic systems tracking around Beaufort Sea low; producing rain.	3 F	1961, 1966, 1973 and 1974
STUDY PERIOD	PERIOD OF MASS BALANCE RECORDS		-	1961-77
I	MELT SUPPRESSION	Seasons dominated by elongated North American sector vortex.	4 B	1972
I/IIs	*Hypothetical Decade of Melt Suppression and Summer Accumulation*		*6 C*	*I and IIs (5/5)*
IIs	SUMMER ACCUMULATION	Season dominated by motion of vortices across QEI from Polar Ocean; producing snow.	5 B	1964

TABLE 3B: *CLIMATIC AND GLACIOLOGICAL PARAMETERS FOR THE QUEEN ELIZABETH ISLANDS (QEI) FOR VARIOUS PERIODS (EXPRESSED AS ANNUAL VALUES). SEE TABLE 3A. (VALUES BASED ON ACTUAL SEASONS ARE IN* BOLD *TYPE; THOSE CALCULATED FROM HYPOTHETICAL COMBINATIONS OF ACTUAL SEASONS ARE GIVEN IN ITALICS).*

	MASS BALANCE (kg $m^{-2} yr^{-1}$)					TEMPERATURE (°C)		
NAME	Meighen I. Ice Cap	Devon I. Ice Cap	Percent Melt, 1600-1800 m on Devon I. Ice Cap (%)[1]	Percent of total open water QEI (%)[1]	Equilibrium Line Altitude Devon I. Ice Cap (m)[2]	Mean July for QEI	Mean summer for QEI	Mean for Mass Balance season (September-August) for Resolute Bay
III	-1080	-345	56	70	1510	6.4	3.6	-15.9
III/IIr	*- 598*	*-233*	*41*	*60*	*1374*	*5.1*	*2.7*	
50-yr	*- 305*	*-125*	*26*	*51*	*1214*	*4.3*	*2.2*	
NORMAL	-	-	-	-	-	4.1	2.1	-16.4
IIr	- 115	-125	25	50	1238	3.7	1.8	
STUDY PERIOD	- 109	- 53	16	45[3]	1108[3]	3.8	1.9	
I	+ 55	+102	0	21	800	2.8	1.3	-18.1
I/IIs	*+ 203*	*+136*	*2*	*28*	*705*	*2.4*	*1.4*	
IIs	*+ 350*	*+170*	*4*	*34*	*610*	*1.9*	*1.4*	*-16.8*

[1] After Koerner (1977).
[2] After R.M. Koerner (personal communication).
[3] Based on 14 years (1961-74) of data.

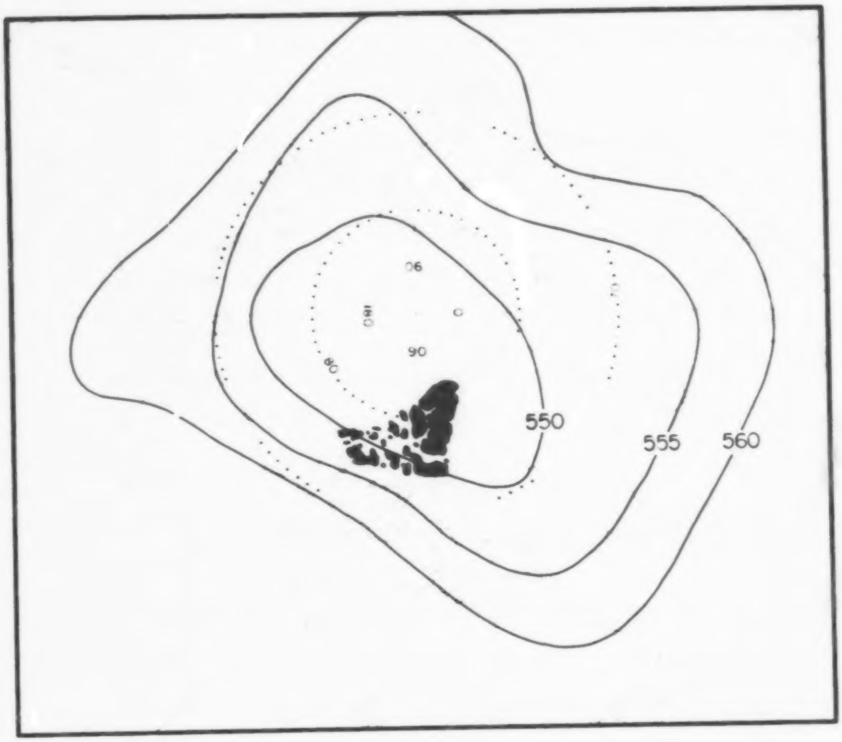


FIGURE 3F: **IIr** - *July 500 mb-pattern for summer seasons dominated by cyclonic systems with tracks which allow intrusion of the warm sector into the QEI, producing rain on the ice caps (***IIr***). Pattern is a graphically-produced mean of the years 1961, 1966, 1973 and 1974.*

Moderate Melt in the QEI (Represented by 1961, 1966, 1973 and 1974):
Frequent Vortex in Beaufort Sea Sector (IIr)

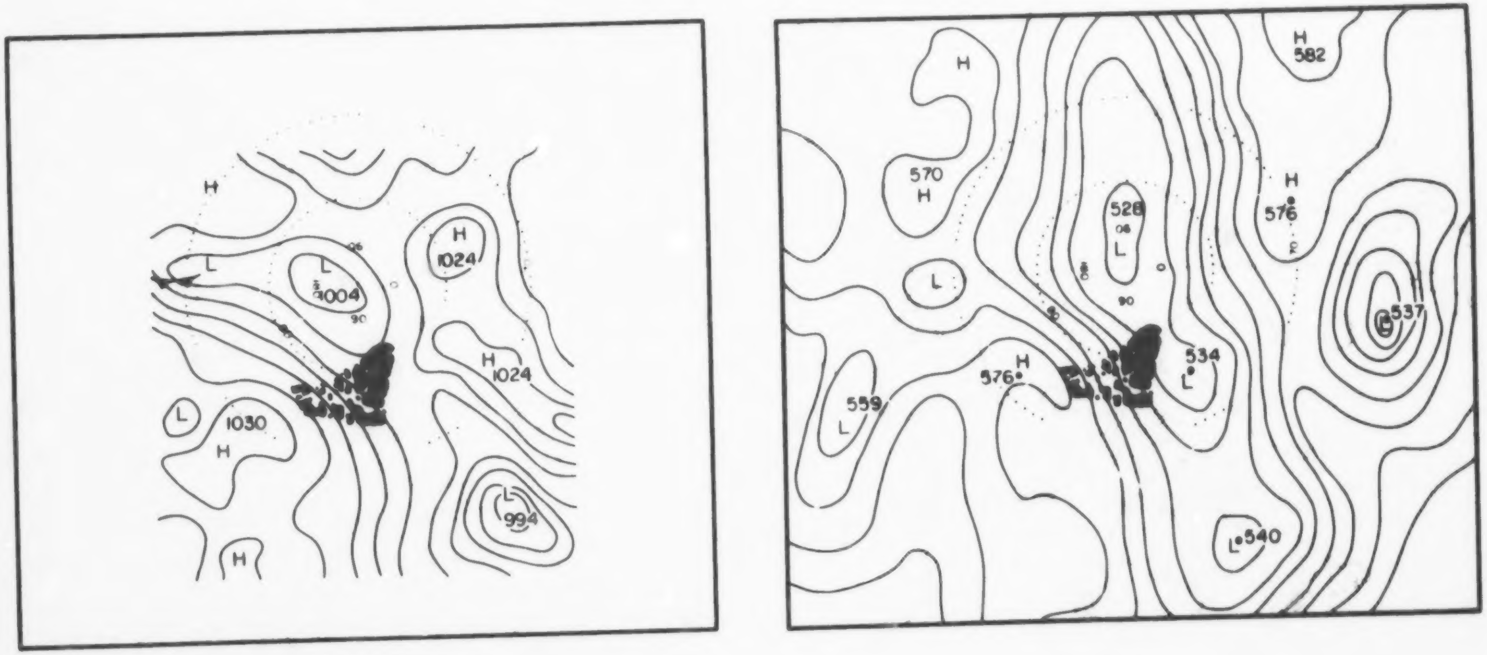
Seasons experiencing 30 to 40% *Type IIr* Tracking Cyclone situations, in combination with both Anticyclonic *(Type III)* and the North American sector vortex *(Type I)* situations, produce positive mass balance conditions throughout the QEI. The greatest melt occurs in regions most frequently in the warm sector of the surface frontal systems. Summer-season precipitation is in the form of rain rather than snow. These combination years are common during 1960-78. The seasons of 1961, 1966, 1973 and 1974 exhibit these conditions on Meighen, Melville and Devon Island Ice Caps, and have been combined to obtain the values of climate and glacier parameters (Table 3) and a mean July 500 mb-pattern for *IIr* seasons (Figure 3F).

Melt Suppression in the QEI (1972):
Elongated Vortex from Pole to Baffin Bay (I)

The summer of 1972 fell in the middle of an 18-month period of below-normal temperatures in the QEI, and followed a winter of vigorous circulation and strong blocking in Europe and Alaska. The North American sector vortex, though weaker than in winter, dominated the summer season. Melt was strongly suppressed when linkage of the Baffin Bay vortex with the Pole or Laptev Sea sector vortex formed an elongated low with below normal 500 mb-heights from Baffin Bay through Nares Strait to the Pole *(Type I;* Figure 4A). The resulting northwesterly flow off the Polar Ocean brought a regional temperature depression of 1.2°C below normal for the summer season. The most negative temperature departures were experienced in the east and under the low. Precipitation, though frequent, averaged only 47% of normal. Values of the climate and glacier parameters for a season dominated by an elongated North American sector vortex *(I)* based on 1972 are given in Table 3, and the 500 mb-July pattern is represented by Figure 4B.

Summer Accumulation in the QEI (1964):
Motion of Vortices into the Islands from the Polar Ocean (IIs)

In June and July of 1964, the synoptic situation in the QEI was governed by the motion of successive 500 mb-vortices from the Laptev and East Siberian Sea sectors through the QEI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L
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1004
H
1024
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1024
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1030
H
L
994
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H
570
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528
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H
576
582
H
559
L
576
H
534
L
537
L
540

FIGURE 4A: **Type I** - *Synoptic pattern for July 3, 1972 (at 12 GMT). Surface pressures (left) in mb and 500 mb-height contours (right) in dekameters (dam). Elongated low from Kara Sea sector across the Pole into northern Baffin Bay. Northwesterly flow over the QEI held minimum temperatures to near freezing. Precipitation was frequent but only at Alert was the accumulation above normal.*

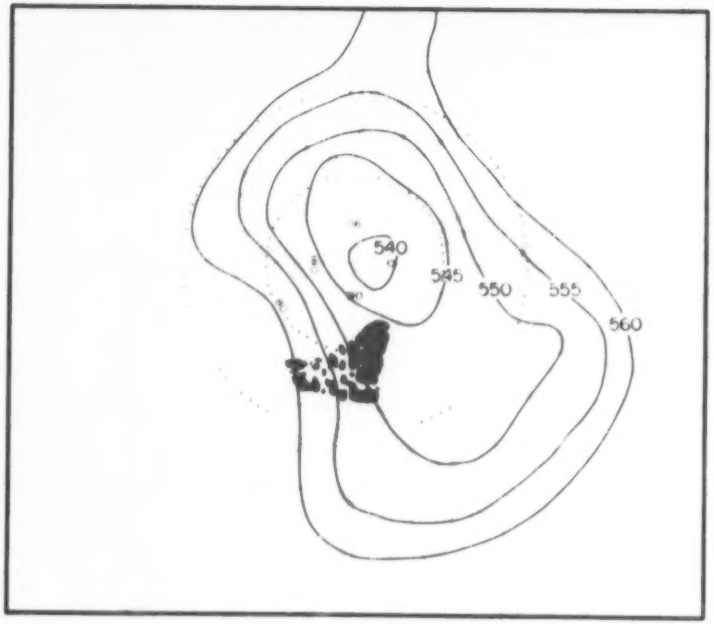
540
545
550
555
560

FIGURE 4B: I - *July* 500 *mb-pattern. Height contours (dam). See* FIGURE 3D.

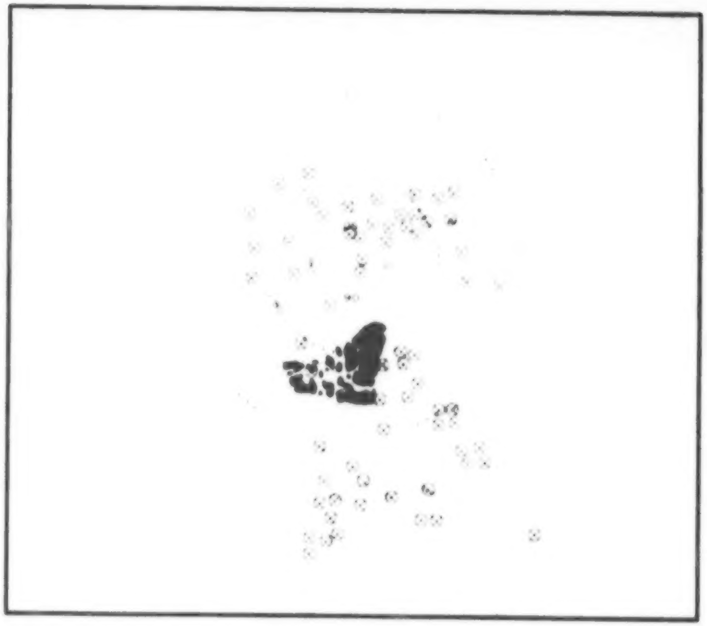

FIGURE 4C: *Positions of* 500 *mb-vortex centres influencing the QEI. See* FIGURE 3C.

in a southeast direction towards Hudson Bay or Baffin Bay-Davis Strait. Figures 5A,C illustrate the tracks of these 500 mb-vortices. On occasion the vortex remained quasi-stationary in the Islands (Figure 5C). These systems appear to have been cold-core lows extending from the surface to the upper troposphere. The surface low occurs directly under the upper vortex as opposed to tracking around it. In the north and central regions of the QEI (which were most frequently under the low), temperature depressions of 3°C were experienced and snow amounts were 300-600% of normal. Summer accumulation, augmented by increased spring accumulation, produced highly-positive mass balance values on all QEI glaciers. Melt was not suppressed to the same degree as in 1972, though the regional temperature anomaly was greater than in 1972. Most regions of the QEI were at one time or another under the influence of southerly flow in advance of the tracking system. This southerly flow was most frequent in the eastern QEI, producing temperatures only 1°C below normal at Alert.

Further study is necessary of the synoptics of summer accumulation seasons *(IIs)* to isolate the distinctive qualities of such seasons. The season of 1964[1] has been used to obtain values of climate and glacier parameters (Table 3) for a season dominated by motion of vortices from the Polar Ocean across the QEI *(IIs)*. The mean July 500 mb-pattern for a *IIs* season is represented by Figure 5B.

Southwest Shift of the Vortex

In both 1972 and 1964, the seasonal temperature maxima were reached with a shift of the 500 mb-vortex to the southwest into Keewatin. This was accompanied by backing (westward motion) of the long-wave pattern which allowed (of was the result of) strengthening of the Alaska and/or Greenland blocking highs. The backing conditions were linked with a weakening of the mid-latitude Westerlies. There also seems to be a connection with motion of the East Siberian-Laptev Sea vortex into the Kara-Barents Sea sector. The significance of this situation to studies of glacial advance is discussed in Alt (in preparation).

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[1] With the exception of mass balance for Devon Island Ice Cap, where the 1976 value is used as it was more positive than the 1964 value, and the synoptic controls were similar (Alt, in preparation).

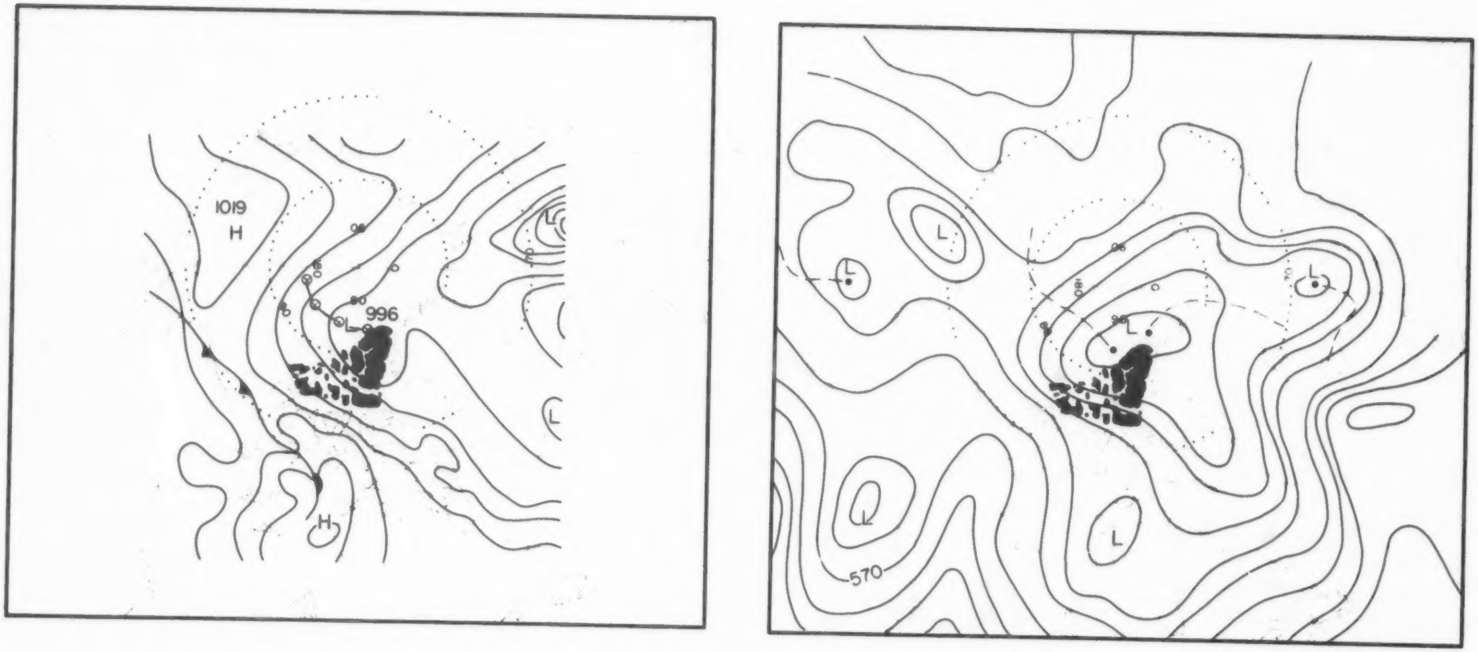


FIGURE 5A: **Type IIs** - *Syncptic pattern for July 29, 1964 (at 00 GMT). Surface pressures (left) in mb and 500 mb-height contours (right) in dekameters (dam). Minimum temperatures were below freezing in the QEI, and snow fell at all QEI stations, (e.g. 4.3 inches (10.9 cm) at Resolute) as the low moved across Ellesmere I. into Baffin Bay.*

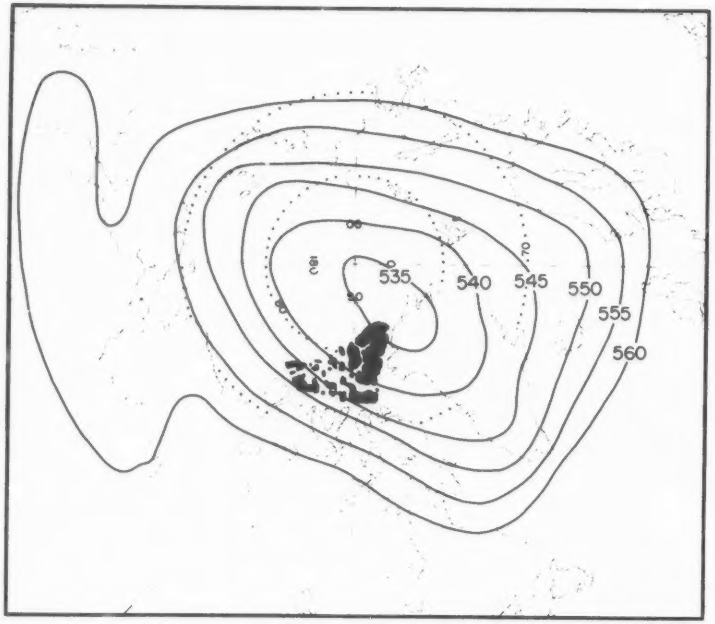

535
540
545
550
555
560
90
180
70

FIGURE 5B: **IIs** - *July mean 500 mb-pattern for 1964. Note the low central heights and strong gradient. Mass balance on QEI ice caps was twice as positive as in 1972.*

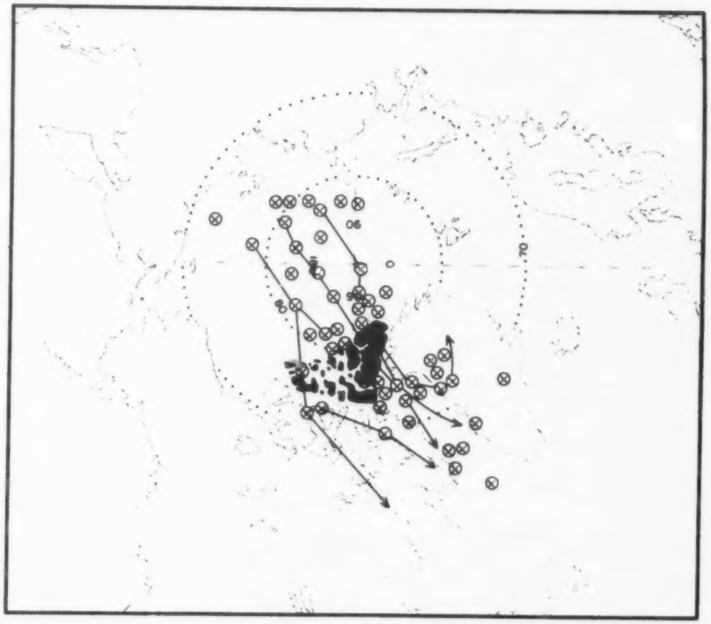


FIGURE 5C: *Positions of vortex centres in 1964, and motion of these vortices. See* FIGURE 3C.

PALEOCLIMATIC IMPLICATIONS

What follows is an attempt to derive a first approximation of the magnitude of variation in climate and glacier conditions that can be effected by presently-occurring synoptic situations. This will, I hope, allow an estimate of the degree to which such synoptic conditions can be used to represent ice-core derived paleoclimatic variations. While it may not prove that such synoptic conditions existed, it should indicate whether we will have to look beyond present synoptic controls to explain climate change in the Holocene. A brief discussion of paleoclimatic evidence from the QEI precedes the discussion of specific periods of climatic extremes during the past 5,000 years.

Paleoclimatic Evidence from the QEI

Synoptic discussions of the present study will not be applied to the period prior to the recession of ice from North America, due to the vastly different surface conditions prevailing up to that time.

Time series of δO^{18} and melt percent from the Devon Island Ice Cap deep cores (Fisher and Koerner 1979) can be used to relate present synoptic conditions to the past 5,000 years in the QEI. Other core parameters, such as volcanic acid layers, microparticles, and pollen concentrations must be integrated into the overall climate picture as work progresses. Figures 7 A-D, reproduced from Koerner and Fisher (1981) and Fisher and Koerner (1981), present the pertinent ice core records.

Following the prolonged postglacial warm period (ca. 8,000-5,000 yr B.P.), the Devon Island Ice Cap δ curve (Figure 7A) peaks around 4,500 yr B.P. From the Climatic Optimum to the present, a cooling of 2 - 2.5°/oo (2.7 to 3.5°C) is evident in the records. Superimposed on this cooling trend, Koerner and Fisher (1981) noted a 2,500-year variation of δ, which can be seen in Figure 7B, of residuals from the trend line. They suggest a link to sun-spot activity (i.e. increased solar constant - increased global temperatures and the converse). The troughs in the δ residuals (temperature minima) coincide with the Little Ice Age and the Post-Optimum Cold Period, while the peaks (temperature maxima) correspond to the Medieval Warm Period and Climatic Optimum.

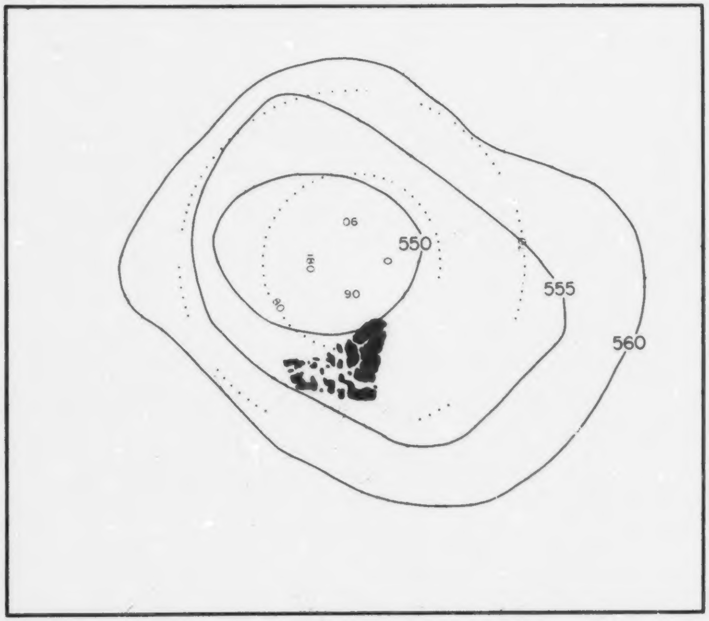


FIGURE 6A: **III/IIr** – *July 500 mb-pattern for hypothetical decade dominated by a combination of Anticyclonic blocking in the QEI (***III***) and a tracking cyclonic systems with warm sector intrusion (***IIr***). The patterns of 1962 and 1957 were combined to produce the* **III** *pattern. The* **III/IIr** *is a graphically obtained mean of the* **III** *and* **IIr** *patterns.*

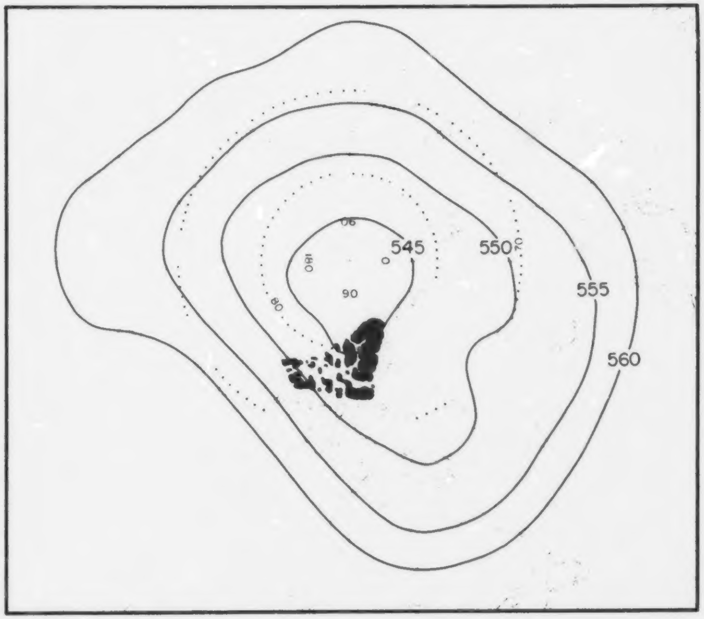
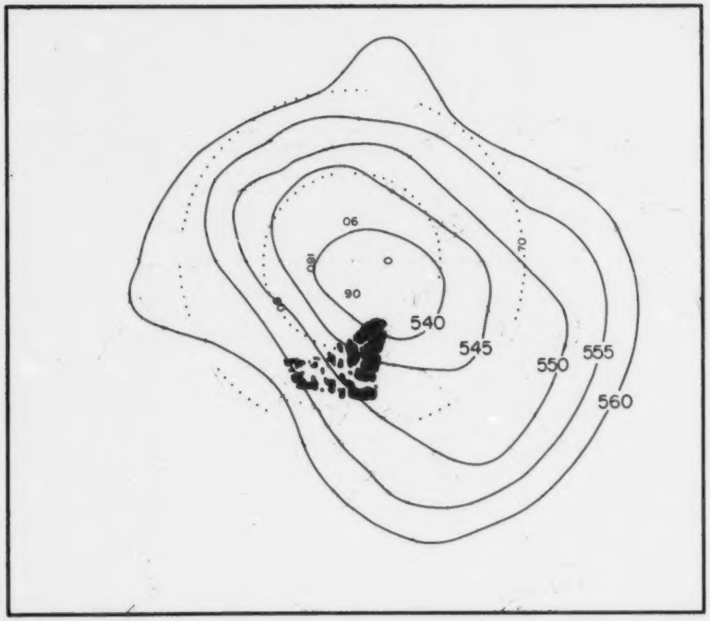


FIGURE 6B: **50 years** – *July 500 mb-pattern for hypothetical 50-year period combining the* **III/IIr** *decades and the mean 1949-1978 pattern in ratio 2/3.*


90
0
180
90
80
70
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555
560

FIGURE 6C: **I/IIs** - *July 500 mb-pattern for hypothetical decade combining summer accumulation on tracking vortices,* **IIs** *and melt suppression* **I**.

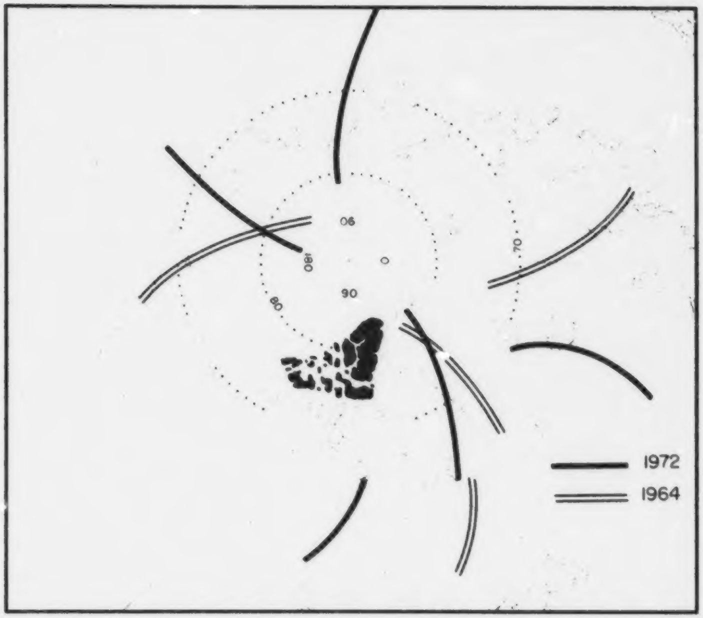
90
0
180
90
80
70
1972
1964

FIGURE 6D: *Trough positions on mean July 500 mb-charts for* **I** *and* **IIs** *seasons.*

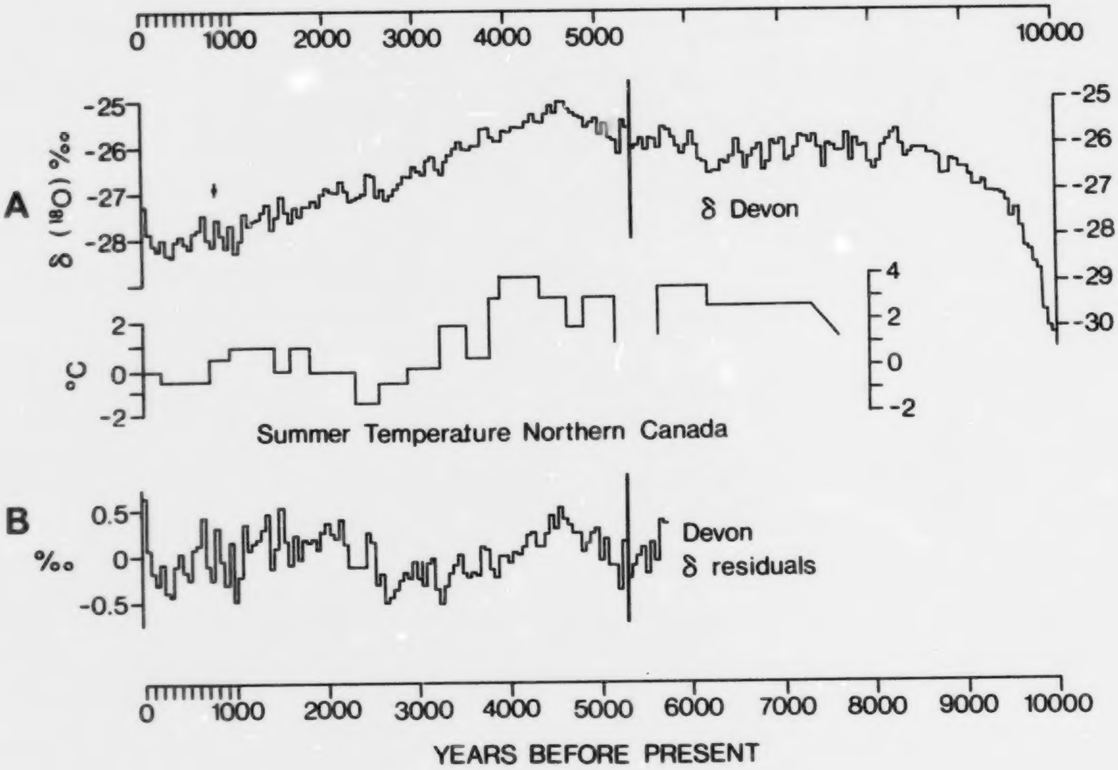

FIGURE 7A: *The upper histogram represents the last 10,000 years of record of $\delta(^{18}O)$ from Devon Island Ice Cap cores. The middle histogram represents summer temperatures of the last 7,500 years in northern Canada as indicated by pollen data (Nichols 1972).*

FIGURE 7B: *The lower histogram represents deviations of values from the 4,000-year trend line for the Devon Island $\delta(^{18}O)$ record. Beyond 5,300 yr B.P., the time-scale is based on cross-correlation with the Camp Century core, which is accurate to within 5%.*

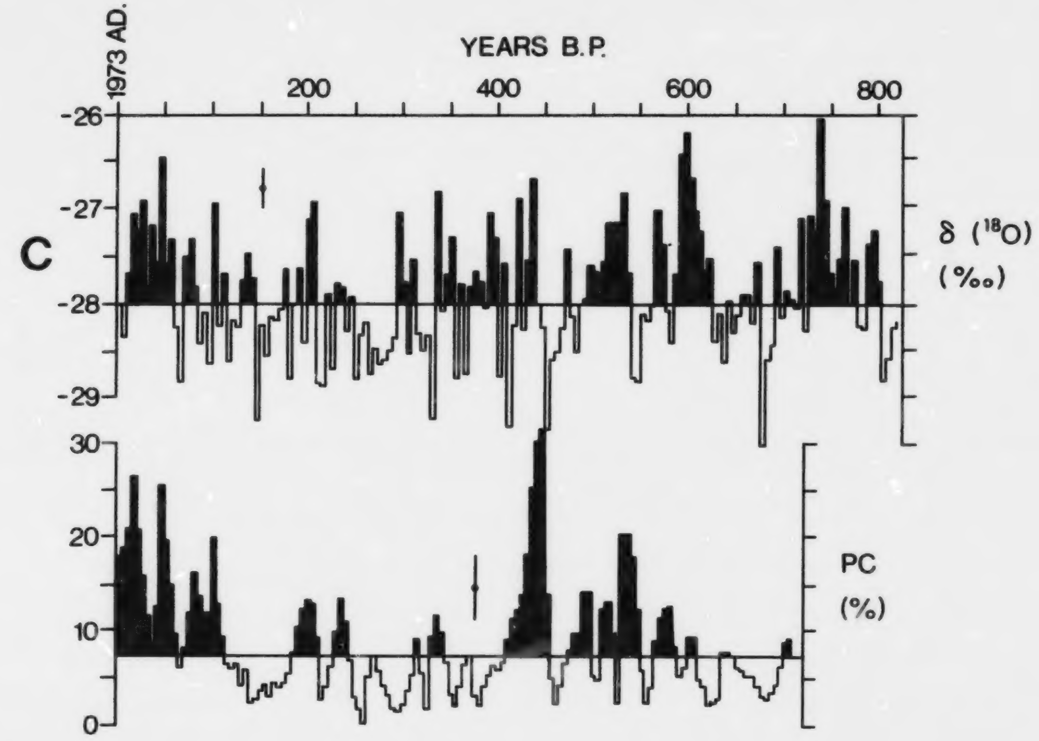

FIGURE 7C: δ(^{18}O), *melt percentage (PC), over the last 700-800 years from Devon Island Ice Cap cores. Blackened portions represent above-average values.*

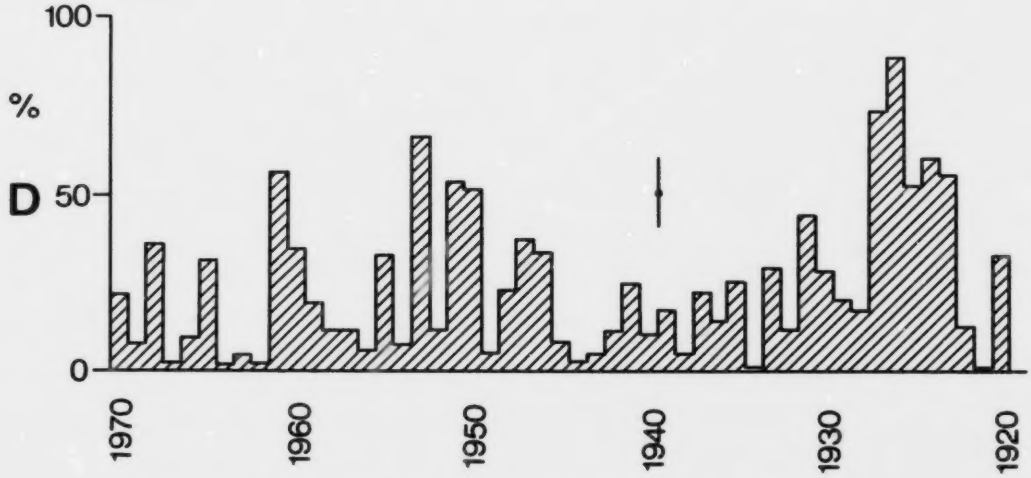

FIGURE 7D: *Devon Island summer melt percentage (PC) from the 1971 coring. The time-scale for the summer melt percentage is exact from 1958 to 1971, but older years could be out by ± 1 year because they are based on a constant accumulation assumption.*

Koerner and Fisher (1981) find a poor relationship between δ and mass balance, and suggest that this results from the complex and often poor relationship between annual temperature (δ) and summer temperature (melt). Variations in the distribution of precipitation over the season (i.e. rates of winter to summer precipitation) further complicates the δ/mass balance relationships. These aspects of the paleoclimatic record are being studied and will be referred to briefly in the following discussions.

Period of Mass Balance Records: 1961 to Present

Figure 7C shows that, while δ values have dropped below the 700-800 year average in recent five-year periods, melt values remain well above average. This relationship indicates that annual temperature (or more accurately the temperature during precipitation events) is lower than average, while the summer temperatures are higher than average. Table 3 shows that the *I* season has lower annual temperatures and higher summer temperatures than the *IIs* season. The *I* season receives less summer snow than the *IIs* season which makes the δ (annual temperature) appear lower than the actual annual temperatures. Both these factors indicate a lack of *IIs* situations over the study period relative to the average for the past 700-800 years.

The Post-1920s Melt Maximum

The post-1920s warm period has received much attention in the literature as it falls within the period of instrumental record in populated areas, though not in the QEI.

For the QEI, a hypothetical decade has been created using five *III* seasons and five *IIr* seasons. Mean seasonal values of the various climate and glacier parameters for this *III/IIr* melt-dominated decade are given in Table 3. The mean July 500 mb-pattern for such a decade is shown in Figure 6A.

Synoptic analysis of 1962 (Alt, in preparation) showed that occurrence of one additional warm-sector situation over Devon Island Ice Cap would be sufficient to increase the 1962 melt to that experienced in the peak year of 1927 (Figure 7D). The period of maximum melt

(1925-30) seen in the melt record (Figure 7D) differs from the 1961-77 average (Table 3) by approximately 20%. The hypothetical *III/IIr* decade (Table 3) produced melt 25% greater than the 1961-77 average. The 500 mb-pattern produced by combining *III* and *IIr* (Figure 6B) is in good agreement with mid-latitude studies of the post-1920s warm period. These show strong, northward-displaced, zonal west-east circulation, and increased import of warm air and water into the Barents and Kara Seas. Dzerdzeevski's (Dzerdzeevski and Sergin 1972) plot of the frequency of zonal (west-east) and meridonal, cross-latitude circulation patterns shows that strong zonal circulation began in the 1911-20 decade and ended in the 1950-59 decade. It is important to note that, within the generally-warm period, extreme seasons and decades occurred at different times in different parts of the world (Lamb 1977). Hemispheric temperatures peak in 1935-38 (Groveman and Landsberg 1979), whereas on Devon Island Ice Cap the δ curve peaks in the 1920s.

The Most Recent 50-year Period: 1925-1974

The ice core δ records are plotted by Koerner and Fisher (1981) as 50-year mean values (Figures 7A,B), but meteorological records are only available in the QEI from 1949. A hypothetical 50-year period was therefore created to represent the most recent 50-year period (1924-1973). Examination of the annual melt record (Figure 7D) shows that the 1925-34 decade and the 1945-54 decade include five seasons of high melt with a background of moderate melt, and can be represented by the hypothetical *III/IIr* decade. The remaining three decades resemble the 1961-77 study period. Values of the climate and glacier parameters have been calculated on this basis for the hypothetical 50-year period (Table 3). The value of melt percent thus calculated (26%) is slightly greater than the measured melt value for the the most recent 50 years (23% from values in Figure 7D), but is well within observation error limits. The 500 mb-pattern for the hypothetical 50-year period (Figure 6C) was deduced by combining the *III/IIr* decade with the 1949-78 mean, weighted in favour of the latter. The mean vortex becomes symmetric about the Pole, with almost equal development of the North American, Norwegian Sea, Laptev[1] and Chuckchi[1] Sea troughs. This hypothetical 50-year period can now be used to compare the most recent 50 years with other maxima in the Devon Island Ice Cap δ record.

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[1] The pattern in the Eurasian sector requires further study to determine whether it has any significance to climatic change in that region.

The Little Ice Age: 400 - 150 yr B.P. (1570-1820 A.D.)

The most recent minimum in the 2,500 year cycle, superimposed as it is on the general downward 5,000 yr δ trend, has effected the most negative δ values of the Holocene (Figure 7A). The 50-year mean δ curve (Figure 7A) reaches a minimum approximately 300 yr B.P., which Fisher and Koerner (1981) estimate to be 1.6°C below the most recent 50-year mean. The corresponding minimum on the Nichols summer temperature for Keewatin (Figure 7A) is only 0.5°C below present. Combining seasons of melt suppression associated with the elongated North American sector vortex *(I)* with seasons of summer accumulation due to motion across the QEI of Polar Ocean vortices *(IIs)* equally into a hypothetical positive mass balance (cold) decade, produces values of climatic and glaciological parameters shown in Table 3B. This *I/IIs* decade is capable of lowering the QEI summer season temperature by 0.7°C and the July temperature by 1.7°C.

Almost no melt occurred at the drill site on Devon Island about 250 yr B.P. (Figure 7C), a condition which can be achieved by complete dominance of elongated North American sector vortex seasons *(I)*. The δ values were also low during this period suggesting cold annual temperatures and/or a lack of summer precipitation. The melt minima between 350 yr B.P. and 380 yr B.P., on the other hand, coincide with above-average δ values (Figure 7C) suggesting warm annual temperatures and/or increased warm season accumulation. These conditions can be reproduced by complete dominance of *IIs* seasons. The strongly-positive mass balance conditions of the *IIs* seasons would be needed to achieve the equilibrium line altitude (ELA) lowering of 450 m deduced by Andrews (1972, p. 56) for Baffin Island during the Little Ice Age. Thus, the evidence suggests that summer accumulation conditions *(IIs)* dominate the initial period of the Little Ice Age and are followed by strong summer melt suppression *(I)* and cold winters.

The combined *I/IIs* 500 mb-pattern (Figure 6C) illustrates some of the problems inherent in dealing with means of distinctly different synoptic situations. Figure 6D shows the individual trough positions of the *I* and *IIs* seasons. These are difficult to distinguish on the mean chart. The 1972 pattern combines the elongated low from the Laptev Sea sector to Baffin Bay with the cut-off low in Keewatin which produced the seasonal temperature maximum in the QEI. The result could be mistaken for a deepening and shift westward of the North American trough. The 1964 pattern would be more accurately represented by a series of deep vortices joined to show the progression of these around the Polar Basin and across northern Ellesmere Island to Baffin Bay.

In spite of these drawbacks we can see three of the features discussed by Lamb (1977) with regard to mid-latitude circulation during the Little Ice Age:

(1) Expanded vortex with mean July central heights below 540 dam.

(2) Strong flow (i.e. strong winds at all levels) - particularly northwest of the QEI.

(3) Markedly meridional (cross latitude) flow in the QEI and anticyclonic blocking in the Beaufort Sea sector.

Lamb also deduced a 50-year periodicity of anticyclonic blocking and increased variability of climate. Comparing the trough and ridge positions of the *I* and *IIs* seasons (Figure 6D) shows a common trough along the west coast of Greenland. The other positions do not coincide. Alternation between these patterns would produce variable conditions elsewhere in the Arctic Basin. This illustrates why periods of maximum cooling or glacierization did not occur simultaneously around the Basin (Lamb 1977). Extremes resulted when any particular region was under the influence of *I* or *IIs* conditions respectively.

The Medieval Warm Period: 2,000 - 1,000 yr B.P.

Beyond 800 yr B.P., we must rely on the δ records. The Devon Island Ice Cap 50-year δ residual curve (Figure 7B) shows a 0.5 °/oo (0.8°C) warm fluctuation around 1,500 yr B.P. Comparison with the most recent 50-year period shows the maxima to be of similar magnitude on the residual curve and within the error bar on the actual δ curve. The present maximum is sharper than its medieval counterpart; however, within 100 years of the main Medieval maximum there occurred 50-year periods which fell below the trend line.

Lamb's (1977) mid-latitude studies show temperature differences between the medieval warm period and present decades of the order of 1°C in England, and it is interesting to note he places the greatest warming in the summer. China also exhibits a 1°C warming. The half-century peak values do not coincide temporally from one region to the next. As in the post-1920's warm period, the QEI reach their maximum warmth sooner than China or England. In fact, the progression of the peak warming westward around the globe from northeastern North America (1,500 yr B.P.) to China (1,200 yr B.P.) and finally to England (800 yr B.P.) resembles King's (1974) 600-year magnetic anomaly cycle.

Post-Optimum Minimum (3,000 - 2,500 yr B.P.)

The δ residual curve (Figure 7B) shows a broad minimum between 3,000 and 2,500 yr B.P., which is equal in magnitude to the Little Ice Age minimum. Actual δ values at the minimum (Figure 7A) are however similar to the most recent 50-year period. In other words, the annual or precipitation season temperatures are similar to those in this century. The Meighen Ice Cap core indicates that the ice cap covered most of the island during the earlier part of this period and experienced a positive balance with several short periods of negative balance in the latter part of the period (Koerner and Paterson 1974). Warm winters and cool wet summers, such as experienced in the *IIs* season of 1964, could duplicate such a situation. The mean temperature of the winter accumulation season and melt season of 1964 at Resolute (September 1963 - May 1964) was -16.4°C. Table 3 shows that the hypothetical 50-year period, which represents the most recent 50 years, produced similar summer conditions to the 1949-70 normals. The mean annual temperature for the 1941-70 normal period is similar to that of 1964. It is thus possible to envision annual temperatures, similar to the most recent 50 years, occurring with *IIs* accumulation summers producing strongly-positive mass balance conditions. The increased warm precipitation would also contribute to the generally higher δ values. The mean summer circulation pattern for the early part of the period in the QEI might be expected to resemble *IIs*, and to extend later into the fall than at present. Gradually the *I* melt suppression pattern would become more dominant, though winters remained relatively short and warm.

The Climatic Optimum (5,000 - 4,000 yr B.P.)

Between 5,000 and 4,000 yr B.P., δ values reached a peak of 2 - 2.5 °/oo greater than recent times, suggesting a temperature difference of 3 to 4°C between the most recent

50-year period and the Climatic Optimum in the QEI. Nichols' (1972) curve of summer temperature in northern Canada shows a similar shape, with the peak between 4,000 and 4,500 yr B.P., and indicates summer temperatures in Keewatin 3 - 3.5°C higher than today. Table 3 shows that complete dominance of *III* produces July temperatures only 2.1°C greater than the hypothetical 50-year period. It appears then that dominance of *III* anticyclonic conditions as experienced since the early 1960s is not capable of duplicating conditions existing during the Climatic Optimum in the QEI. However, Figure 7B shows that the magnitude of the residual from the δ trend for the optimum is similar to that for the most recent 50 years and the Medieval Warm Period. Therefore, it seems reasonable to treat the Climatic Optimum in the QEI as a maximum in the 2,500-year cycle superimposed on the final phase of the postglacial warming.

The final phase of the postglacial warming is depicted by Lamb (1977) as a time of zonal (west-east) flow and weakened thermal gradient on a hemispheric scale. The effect in the QEI, which lies under the North American cold vortex in winter, would be warmer winters and longer summers.

Superimposed on this generally warm atmosphere, one can hypothesize summer synoptic patterns similar to those responsible for the medieval maximum in the 2,500-year cycle. Combining the hypothetical *III/IIr* decade with the rise in 500 mb heights and decreased gradient proposed by Lamb (1977), one can envision a 500 mb-July pattern such as shown in Figure 8. The 555 dekameter (dam) contour encircles the Polar Ocean, and the 560 contour shifts north as far as northern Baffin Island. The QEI "became" part of the North American continent in summer.

Comparison of Negative and Positive Mass Balance Decades

The fundamental differences in the circulation pattern of the hypothetical *III/IIr* decade (negative mass balance) and the hypothetical *I/IIs* decade (positive mass balance) can be seen in Figure 9 of 550 dam height contour. The positive balance vortex, thus represented, is at least twice as extensive as the negative balance situation.

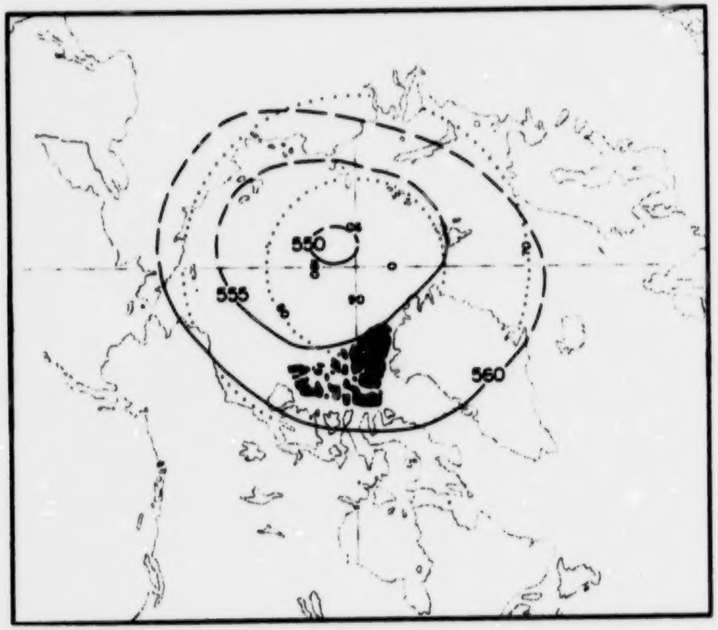

FIGURE 8: *Hypothetical July 500 mb-pattern for the Climatic Optimum in the QEI. Graphically produced from 1962 and 1957 July pattern and 1000-500 mb thickness change over the QEI deduced by Lamb (1977).*

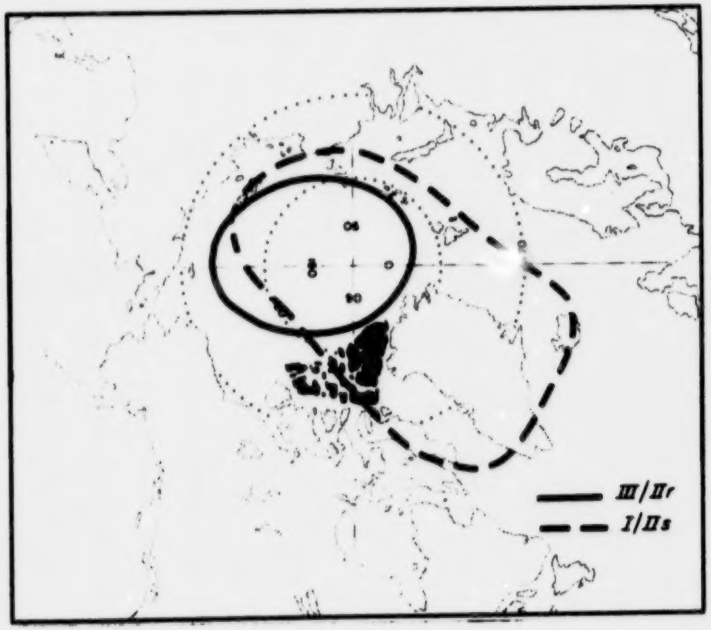

FIGURE 9: *550 dam-height contour for* III/IIr *and* I/IIs *decades.*

Atmospheric flow for the *I/IIs* decades is off the Polar Ocean, whereas for the *III/IIr* decade it enters the islands from the southwest off the Beaufort and Bering Seas.

Table 4 shows the average mass balance conditions that the hypothetical *III/IIr* and *I/IIs* decades would produce as maximum and minimum respectively of the 2,500-year cycle. The calculated average mass balance values are strongly negative for both Meighen and Devon Island Ice Caps contrary to evidence from the ice caps (Koerner and Fisher 1981). Substituting the hypothetical 50-year period (most recent 50 years) for the maximum gives near equilibrium average mass balance value for Devon Island Ice Cap, whereas Meighen Ice Cap mass balance remains negative. Regional variations in the effectiveness of individual synoptic patterns are responsible for this difference and are beyond the present discussions. Replacing the *I/IIs* decade with complete dominance of *IIs* would produce a positive average balance on both ice caps. This is a further indication of a prolonged period dominated by *IIs* during the Little Ice Age, and may also suggest increased intensity of *IIs* seasons as compared to today.

TABLE 4: *MASS BALANCE AND TEMPERATURE AVERAGES PRODUCED BY VARIOUS COMBINATIONS OF HYPOTHETICAL PERIODS FOR THE QUEEN ELIZABETH ISLANDS (QEI) (SEE TABLE 3 FOR CHARACTERISTICS OF THE PERIODS).*

PERIOD	MASS BALANCE (Kg $m^{-2}yr^{1}$)		
(Maximum-Minimum)	Meighen I. Ice Cap	Devon I. Ice Cap	MEAN JULY TEMPERATURE (°C) FOR THE QEI
III/IIr* to *I/IIs	-395	-112	3.8
50-yr* to *I/IIs	-102	- 4	3.4
50-yr* to *IIs	+ 45	+ 45	3.1

CONCLUSIONS

Synoptic analogs created from present extreme conditions for the QEI are capable of reproducing the magnitude of observed climatic differences between the 1961-77 study period and periods of extreme conditions such as the most recent 50 years, the Little Ice Age, and the Medieval Warm Period. Beyond this, the down-core (i.e. back in time) warming must be considered, which greatly magnifies the degree of speculation involved.

Quantitative studies of the effect of the ratio of warm to cold accumulation on the δ values and of the relationship between annual (δ) and summer (melt) temperature has been initiated to allow better estimates to be made of the magnitude of differences attributable to summer circulation patterns.

There is no proof that the synoptic patterns discussed in the paper are the only ones capable of causing the temperature changes deduced from ice-core oxygen isotope records. Continued monitoring of present QEI climate and mass balance may well record new extreme situations. In fact, the 20-year period of mass balance records demonstrates a low frequency of *IIs* summer accumulation seasons and possibly decreased intensity within this pattern relative to the last 3,000 or 4,000 years. Considerably more effort is needed in understanding the nature of these *IIs* seasons, the moisture source, the tracks, and the reason for continual motion of the vortices into the QEI from the Polar Ocean.

The 500 mb-July height patterns presented apply only to the QEI, though they have been drawn to include the whole Arctic Basin due to the importance of the circumpolar vortex in the discussions. The QEI situations must be related to the circulation characteristics around the Arctic Basin, to existing studies of the North American trough, and to the wealth of mid-latitude and hemispheric circulation studies. Numerical methods will be introduced into the study to assist in this and in the examination of the 1950s decade. Regional variations within the QEI are presently under investigation.

Techniques used in the present study could be applied to other parameters such as seasonal variations in sea ice, flora or fauna. The critical months would differ from mass balance studies and appropriate combinations of climatic parameters would replace temperature and accumulation as the significant climatic elements. The magnitude of variabilities associated with distinct synoptic situations can also be used to assess the range within which future climatic change can be expected to fall.

This study shows that we cannot rule out changes in frequency of occurrence and intensity of present synoptic systems in discussion of Holocene climatic change. The hypothetical decade concept may help unravel interrelationships between various core parameters, if only by providing a starting point for discussion. Finally, the very fact that it is possible to use these techniques emphasizes the magnitude and importance of season-to-season variability of climate in the QEI.

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PRELIMINARY ANALYSIS OF SEA-ICE CONDITIONS IN THE LABRADOR SEA DURING THE NINETEENTH CENTURY

John Newell[1]

INTRODUCTION

The first documented observations of sea-ice conditons off the Labrador coast were made in June 1534 by John Poullet, a member of Jacques Cartier's first expedition to North America (Macpherson 1981). Since then, many visitors to Labrador have recorded their impressions of the sea-ice they encountered. This paper gives a preliminary analysis of many of these historical documents from the nineteenth century, and uses this material to describe the pattern of sea-ice cover in the Labrador Sea. In addition, nineteenth century ice conditions are compared with present average and extreme ice limits. The material analysed includes published accounts of missionaries, traders, government officials and private expeditions. Newspaper reports and ships' logs have not been extensively searched. This material is currently being analysed to expand the data base.

PRESENT ICE CONDITIONS

The present pattern of ice cover along the Labrador coast has been described in a number of publications (Table 1). After a review of these publications, the ice atlas "Weekly Median and Extreme Ice Edges for Eastern Canadian Seaboard and Hudson Bay" (Sowden and Geddes 1980) was selected to represent present normal conditions. This atlas was selected because: (a) it covers the entire study area; (b) it gives weekly positions of the median and extreme ice edges; and (c) it is based on reliable data. The median ice edges shown in this publication are derived from 10 years of data for the period 1964 to 1973, whereas the extreme ice limits are based on 15 years of data for the period 1964 to 1979. Throughout this paper whenever nineteenth century ice conditions are compared with present normals, these normals are based on the maps presented by Sowden and Geddes (1980). This atlas also forms the basis for the following brief description of present ice conditions in the Labrador Sea.

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TABLE 1: *PUBLICATIONS GIVING PRESENT SEA-ICE LIMITS FOR THE LABRADOR SEA.*

SOURCE	PARAMETERS	FREQUENCY	COVERAGE
FENCO Consultants Limited (1978)	Mean concentration	Monthly	52°N - 84°N
Fraser (1975)	Clearing dates	Weekly	45°N - 70°N
Markham (1980)	Mean and extreme limits, and mean concentration	Bi-weekly	41°N - 55°N
Meserve (1974)	Mean limits by concentration, and extreme limits	Monthly	40°N - 70°N
Sowden and Geddes (1980)	Mean and extreme limits	Weekly	45°N - 63°N
U.S. Hydrographic Office (1955)	Mean limits	Monthly	40°N - 90°N
U.S. Navy Oceanographic Office (1968)	Mean limits by concentration, and extreme limits	Monthly	40°N - 70°N

The ice regime of the Labrador Sea consists of the Labrador pack, which is a mixture of ice carried south from Baffin Bay (West Ice) and ice flowing out of Hudson Strait, and the Storis, which is ice formed off East Greenland that rounds Kap Farvel and flows northward along the West Greenland coast (Figure 1). The Storis is not considered here, since its fluctuations during the study period have been documented by Speerschneider (1931).

New ice formation normally starts in the sheltered bays and fjords of northern Labrador in November and by late December pack ice completely encloses the coast, extending as far south as the Grand Banks. During winter this ice varies in width from tens of kilometres to over 500 km. The width of the ice stream depends on prevailing winds and the severity of the winter. Starting in April the width of the ice stream begins to decrease, and by early June the southern limit of pack has retreated northward to the latitude of Southern Labrador (52°N). In a normal year the entire Labrador coast is ice-free by late July, but this can occur as early as late June or can be delayed until late August. The pattern of ice clearing along the Labrador coast normally involves the formation of a shore lead along the

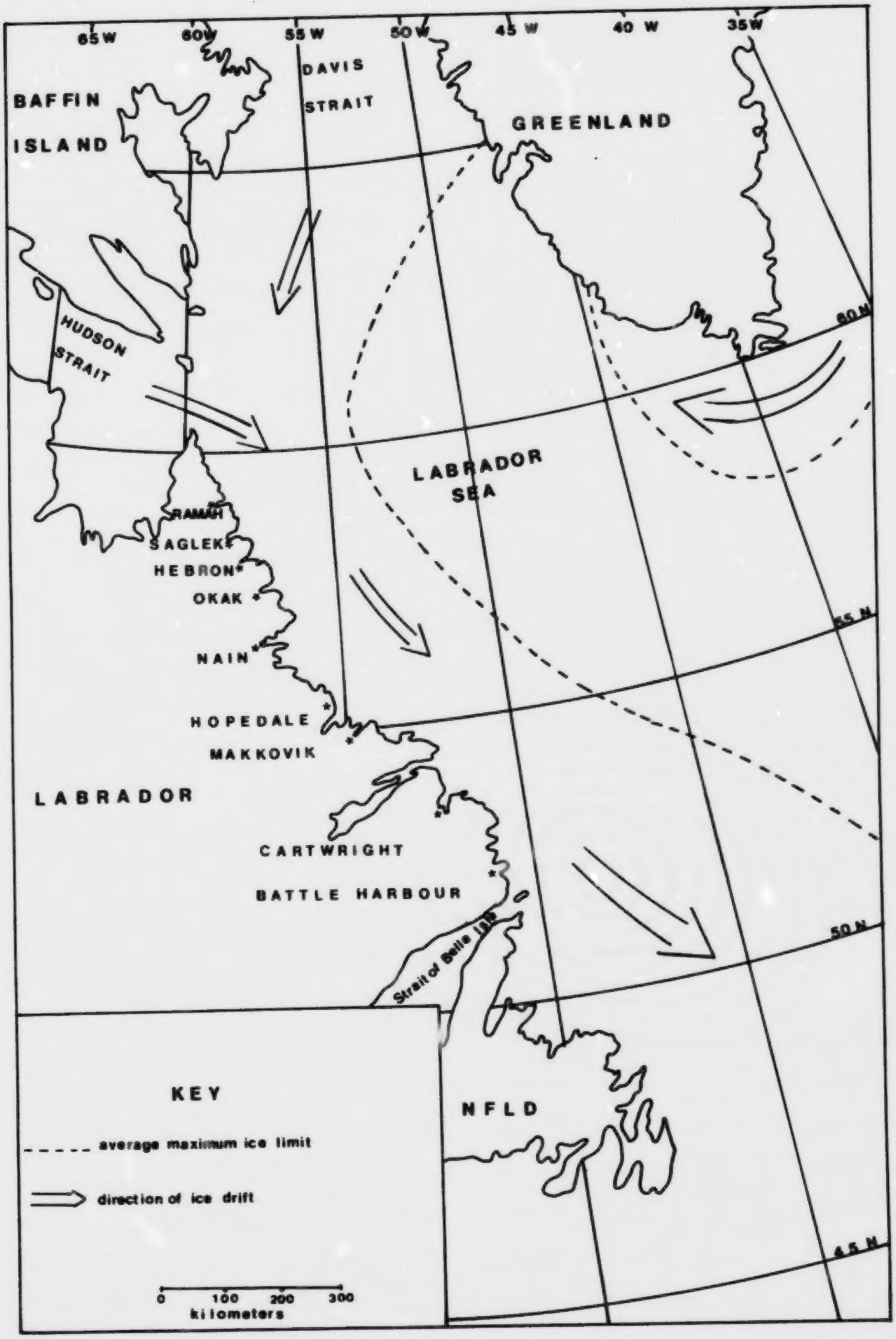
65W
60W
55W
50W
45W
40W
35W
BAFFIN ISLAND
DAVIS STRAIT
GREENLAND
HUDSON STRAIT
60N
LABRADOR SEA
RAMAH
SAGLEK
HEBRON
OKAK
NAIN
55N
HOPEDALE
MAKKOVIK
LABRADOR
CARTWRIGHT
BATTLE HARBOUR
Strait of Belle Isle
50N
NFLD
45N
KEY
average maximum ice limit
direction of ice drift
0
100
200
300
kilometers

FIGURE 1: *Study area.*

coast. This lead usually appears from one to four weeks before the actual date of clearing, and is most common along the southern Labrador coast. The formation of this lead makes it difficult to document the pattern of ice-clearing using data from shore stations.

SOURCES OF INFORMATION

The most complete source of data on ice conditions in the Labrador Sea during the nineteenth century is records of the Moravian missions in Northern Labrador. The first Moravian mission was established at Nain in 1770 and was followed by missions at Okak in 1776, Hopedale in 1782, Hebron in 1830, Ramah in 1871 and Makkovik in 1898 (Figure 1). Most Moravian material used here was extracted from the Periodical Accounts, which are a series of annual reports describing activities at each station. These reports contain two types of ice information. The first type involves references to ice conditions observed from the stations. These observations include references to sightings of pack ice offshore and to the state of landfast ice. Material relating to the landfast ice is not considered here. Pack ice observations must be used with caution since the departure of the pack ice from the land may only be the result of the formation of a shore lead. The second type of information contained in the Periodical Accounts includes references to ice conditions encountered by Moravian mission ships, which visited the Labrador coast each year. These ships departed from England each spring and took a northerly route across the Atlantic, generally attempting to make landfall in the latitude of Hopedale. Ice conditions encountered on these voyages provide an excellent indication of the nature and extent of pack ice found offshore. After arriving at the first station, the mission ship would follow the shore lead north or south along the coast visiting the other stations. Since the ship normally kept close to shore, the only references to ice conditions between stations were during periods of easterly winds when the pack ice was forced onshore. After visiting the last station in late September or October, the ship would depart for England. There are few references to ice conditions on the return voyage, because the previous season's ice had normally cleared the coast and the new ice had not yet started to arrive. Since the Moravian missions were all located between 55°N and 59°N, there are few references to conditions beyond these latitudes.

The principal source of data for the area north of 60°N is the analysis of ice conditions for West Greenland compiled by Speerschneider (1931). The majority of references that he gives are for the Storis but there are some references to the West Ice, which is the Davis Strait and Labrador pack. In addition a few observations for this area are contained in a summary of whaling logs compiled by Wakeham (1897).

References to ice conditions south of 55°N prior to 1860 are scarce. This is a result of a number of factors, some of which include: the absence of any long-term missionary activity in this area prior to 1860; the practice of most naval ships of not visiting the coast until after the normal clearing date; and the fact that regular shipping from St. John's was not established until after this date. Most of the data for southern Labrador is centred on the Strait of Belle Isle (which became a major shipping route after 1860) and the major fishing ports from Battle Harbour to Cartwright (Figure 1). Toward the end of the nineteenth century, scientific expeditions sailing from Canada and the Eastern United States started to become a major source of information for the Labrador coast.

Analysis of available documents reveal over 150 references to ice conditions (Appendix 1). Distribution of these references by decade and area is shown in Table 2. For Davis Strait and Southern Labrador there are peaks in the data during the 1860s and 1870s. In contrast, distribution of data for Northern Labrador by decade is more even, with the greatest number of observations being for the decade 1810-1819. The most striking feature of the table is the dramatic rise in the number of observations from Southern Labrador after 1860. The drop in the number of references to ice conditions after 1890 is due to the publishing date of some of the main references used and to a decline in references to ice conditions in the Periodical Accounts after 1890.

TABLE 2: *DISTRIBUTION OF SEA-ICE DATA FOR THE LABRADOR SEA BY AREA AND DECADE 1800-1900).*

NO. OF REFERENCES FOR EACH AREA	DECADE ENDING									
	1809	1819	1829	1839	1849	1859	1869	1879	1889	1899
60°N - 63°N (Davis Strait)	0	4	4	8	4	2	9	9	6	0
55°N - 60°N (Northern Labrador)	2	15	9	11	9	12	8	10	4	4
51°N - 55°N (Southern Labrador)	0	1	1	4	0	2	17	14	13	4
Total	2	20	14	23	13	16	34	33	23	8

The distribution of data by area and season is shown in Table 3. There are no observations from Northern Labrador prior to July, and few observations from other areas prior to June. This distribution reflects the pattern of shipping in the area. Most ships sailing to Labrador would have some information on the normal clearing date and, therefore, most voyages were planned to arrive on the coast during the break-up period. The decline in frequency of observations after August is due to poor weather during this period and the resulting decline in shipping activity. The seasonal nature of the data restricts analysis of ice conditions to the period between the start of break-up and the start of the winter storms (June to October).

TABLE 3: *DISTRIBUTION OF SEA-ICE DATA FOR THE LABRADOR SEA BY AREA AND SEASON (1800-1900).*

	NO. OF REFERENCES/SEASON						
AREA	JANUARY-MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER-DECEMBER
Davis Strait	2	16	19	2	3	2	–
N. Labrador	–	–	42	33	4	2	3
S. Labrador	8	24	20	1	–	2	1
Total	10	40	81	36	7	6	4

ANALYSIS OF ICE CONDITIONS

References to ice conditions in Appendix 1 are coded according to the severity of the ice season. Records of ice conditions more severe than the present normal have been coded as (+), while records less severe than the present normal are coded as (-). Observations indicating conditions beyond today's extremes are coded as (--) or (++), Table 4 shows the most severe ice code recorded each year of the nineteenth century. Seventy percent of all years had an observation with conditions more severe than normal, and 46% of all years had an observation with conditions more severe than today's extreme. If only those years with data are considered, the percentage of years with conditions more severe than normal is 73%. For many decades, 70% of the years had conditions more severe than today's extreme. Note that, for many years, sea-ice conditions may have been more severe than indicated, because most observations do not refer to a final clearing date.

TABLE 4: ***MOST SEVERE ICE CODE FOR THE LABRADOR SEA REPORTED EACH YEAR (1800-1900).***

	YEAR OF DECADE									
DECADE	00	01	02	03	04	05	06	07	08	09
1800-1809	-	-	-	++	+	-	-	-	-	-
1810-1819	-	++	-	-	-	++	++	++	++	++
1820-1829	++	-	-	+	++	++	+	-	+	++
1830-1839	-	+	++	++	++	++	++	++	-	++
1840-1849	++	++	++	-	++	++	+	++	-	++
1850-1859	+	-	+	++	-	++	++	-	+	++
1860-1869	-	++	++	++	++	++	++	+	++	-
1870-1879	++	+	+	++	++	++	+	-	++	+
1880-1889	+	+	+	+	++	+	-	+	++	++
1890-1899	-	+	-	-	-	-	++	+	-	+

+ - Record of ice conditions more severe than present normal.
++ - Record of ice conditions more severe than present extreme.

The exact departure from today's normal clearing data could be calculated for a number of years. These data are presented as part of the ice code in Appendix 1, and the greatest departure from normal for each year is presented in Figure 2. Average departure from normal for data in Figure 2 was 3.7 weeks, which represents a departure of approximately 1.7 standard deviations from today's normal clearing dates.

During several periods in the nineteenth century, ice conditions apparently departed significantly from the average. The most striking case is the number of very severe ice years during the decade 1810 to 1819. The first year in this decade for which data are available is 1811. Periodical Accounts for this year note that the mission ship arrived at Hopedale on September 8 after encountering ice. This indicates a departure from normal of at least nine weeks. Later observations for 1811 indicate that the coast was likely clear of ice by the end of September. There were no observations of ice conditions for the next three years. In 1814, the Strait of Belle Isle was reportedly clear of ice by July 4. In 1815, there was a report that ice was still off Hopedale on July 19. Neither record indicates particularly severe ice conditions, but an observation by the captain of the Mission ships in 1817 indicates that there were unusual quantities of ice on the coast during both of these years.

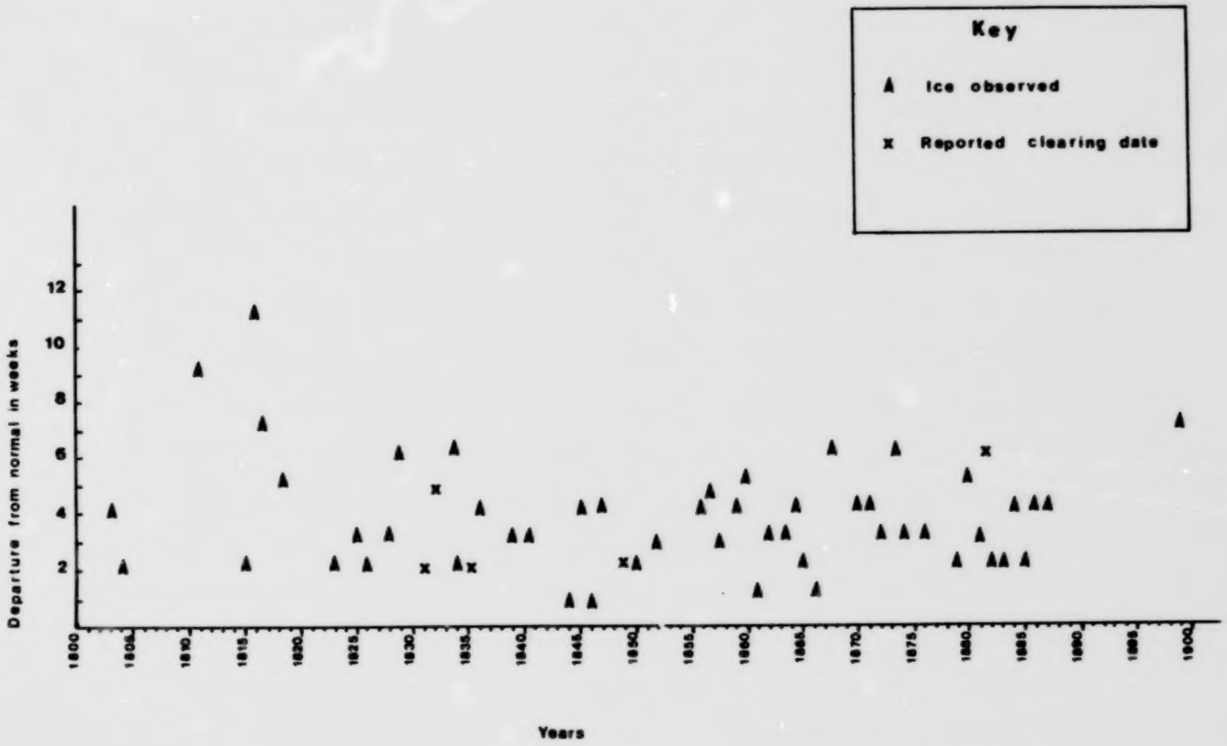

FIGURE 2: *Annual maximum departure from normal for Labrador clearing dates.*

The most severe ice year recorded was 1816. Moravian records for that year indicate that the Mission ship first encountered ice 200 miles (322 km) from land on July 16. It then tried to reach all three stations but was forced back by ice. It finally succeeded in entering Okak on August 29. After departing Okak, the ship tried to reach Nain and, after much trouble with ice, finally succeeded on September 22. It then tried to reach Hopedale but was forced to turn back by ice on October 3. Considering that, in a normal year, new ice starts to form along the Labrador coast in late November, possibly ice remained on the coast until freezeup in 1816. The nearest location where this can occur today is Home Bay on the east coast of Baffin Island (68°N, 68°W), but mean summer temperatures in this area are more than 7°C lower than those on the Labrador coast.

The Labrador coast was not the only area experiencing severe ice and weather conditions in 1816. In the northeastern United States, 1816 was referred to as the year without a summer (Stommel and Stommel 1979). Ice conditions in Hudson Strait were also more severe than normal. Analyses of logs of Hudson's Bay Company vessels (Faurer 1980) show that 1816 was the only year in the nineteenth century in which a return voyage from Hudson Bay was impossible, apparently due to severe ice conditions.

In 1817, the Northern Labrador coast was clear of ice by August 13, but considerable quantities of ice were still south of Okak on this date. The last reference to ice conditions for that year indicates that ice was still off Hopedale on August 20. Even though sea ice cleared earlier than in 1816, the captain of the Mission ships reported that in no year since the start of the mission in 1769 "... did the ice appear so dreadfully on the increase". The colour of the ice was different from that normally seen and the thickness of the fields was immense (Periodical Accounts, Volume 6).

Ice conditions in Davis Strait and Hudson Strait were also more severe than normal in 1817. Speerschneider (1931) notes that in 1817 there was only a narrow channel between the Storis and the West Ice in the southern part of Davis Strait, and that the ice remained in the Strait during most of the autumn. In Hudson Strait, ice conditions in 1817 were less severe than 1816, but it was still one of the most severe ice years on record (Faurer 1980).

Periodical Accounts for 1818 note that the Mission ships arrived at Hopedale on August 4 without encountering ice. This suggests that ice conditions were not extremely severe by nineteenth century standards. In Davis Strait, ice conditions were severe in June, but were only slightly more severe than today's normals in July. Farther south at St. John's, weather conditions in the winter of 1818 were more severe than in the recollection of the oldest inhabitants. In April of that year, St. John's harbour froze to a thickness of 3 to 5 feet (0.9 - 1.6 m) (Anspach 1819). By comparison St. John's harbour seldom freezes today - even in the most severe winters.

The final year of this decade was also marked by severe ice conditions in coastal Labrador. On August 20, 1819 the coast at Okak was still choked by ice, and ice did not leave Hopedale until this date. Farther north in Cumberland Sound on southern Baffin Island (65°N), ice conditions seem to have been relatively normal by today's standards.

The years subsequent to 1819 were not characterized by any departures from the normal comparable to those occurring during the decade 1810 to 1819. The years 1820 to 1824 appear to have been relatively mild ice years off Labrador. The few references to ice during this period indicate that conditions were only slightly more severe then today's normals. Periodical Accounts describe winters during this period as being not very severe, or moderate. The period 1825 to 1839 was slightly more severe - the years 1833 and 1836 being considerably more severe than normal. In 1833 the captain of the Mission ships described ice conditions as the most severe in the 28 years of his experience. Again in 1836, the captain described the voyage as the most hazardous since 1816. The period 1840 to 1860 was characterized by conditions slightly more severe than the nineteenth century average, but with periods of slightly better ice conditions. Robinson (1889) states that the older masters considered ice conditions to be less severe after 1860, but examination of Figure 2 does not confirm this. The decades 1860 to 1880 seem to have been as severe, if not more severe, than the previous decades. Following 1880 ice conditions improved considerably.

SUMMARY

This study shows that, during the nineteenth century, ice conditions in the Labrador Sea were significantly more severe than present normals and that, for at least 46% of the years, conditions were more severe than the present extremes. Also, ice conditions during several years in the decade 1810 to 1819 were significantly more severe than conditions in the remainder of the nineteenth century. During at least one of these years (1816), likely the sea ice had not completely cleared the coast by the start of the next ice season. I make no attempt to relate these changes in ice conditions to changing climatic conditions during the nineteenth century, or to use the ice conditions to estimate climatic conditions. I am currently investigating these relationships. Research is continuing in order to increase the fund of information on ice in the Labrador Sea during the nineteenth century and to extend analysis of the data into the eighteenth and twentieth centuries.

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APPENDIX 1: *REFERENCES TO ICE CONDITIONS ON THE LABRADOR COAST DURING THE NINETEENTH CENTURY.*

CODE[1]	YEAR	DATE	REMARKS (REFERENCE)
++(4)	1803	August 10	Mission ship reached Okak after being delayed for three weeks by ice. (Periodical Accounts).
+(2)	1804	July 20	Mission Ship reached Hopedale after being prevented from reaching Okak by ice. (Periodical Accounts).
+(9)	1811	September 8	Mission ship reached Hopedale after encountering ice. (Periodical Accounts).
-	1811	Late August	Extraordinary quantities of drift ice at Nain which did not depart until this date. (Periodical Accounts).
-	1811	August 2	Hudson Strait open. (Kohlmeister and Kmoch 1814).
-	1811	Late September	Coast north of Okak free of ice. (Kohlmeister and Kmoch 1814).
++	1813	April	The West Ice was lying off Godthaab till the 26th. (Speerschneider 1931).
-	1814	July 4	Strait of Belle Isle ice free. (Chappell 1814).
+(2)	1815	July 19	Mission ship arrived at Hopedale through drift ice which encircled the coast. (Periodical Accounts).
+(2)	1816	July 16	Mission ship met ice 200 miles (322 km) from the coast. (Periodical Accounts).
++(16)	1816	August 29	Mission ship arrived at Okak. The coast was still blocked by ice. (Periodical Accounts).
++(9)	1816	Late September	Mission ship twice forced back by ice on voyage to Nain. (Periodical Accounts).
++(11)	1816	October 3	Mission ships unable to reach Hopedale due to ice. (Periodical Accounts).
++	1817	Summer	In southern Davis Strait there was only a narrow channel between the Storis and the West Ice. (Speerschneider 1931).
+(5)	1817	August 20	At Hopedale the coast is still blocked by ice. (Periodical Accounts).
-	1817	November 22	Ice filled Hopedale Bay. (Periodical Accounts).
-	1817	October 28	Sea at Okak froze, this was early. (Periodical Accounts).
-	1818	August 4	Mission ship arrived Hopedale without encountering ice. (Periodical Accounts).
++	1818	June 11	Disko Bay filled with ice. (Speerschneider 1931).

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[1] See text for explanation of symbols. Numbers in brackets following symbols indicate departure from normal in weeks.

APPENDIX 1: *REFERENCES TO ICE CONDITIONS ON THE LABRADOR COAST DURING THE NINETEENTH CENTURY*. (Cont'd)

CODE	YEAR	DATE	REMARKS (REFERENCE)
+	1818	July	The eastern edge of the middle pack was lying in Latitude 66-67°N and Longitude 57-60°W. (Speerschneider 1931).
-	1819	June	The West Ice was 100 miles (161 km) from the coast south of Cumberland Sound. (Speerschneider 1931).
+(4)	1819	August 20	At Hopedale no open water in sight until this date. (Periodical Accounts).
++	1820	July	The West Ice came rather close to the coast of Greenland. (Speerschneider 1931).
-	1820	July 10	At 53°46'N no ice noted. (Robinson 1889).
-	1822	July 18	Mission ship arrived July 18. No ice in sight from Hopedale. (Periodical Accounts).
(2)	1823	July 26	Mission ship beset by ice off Hopedale from July 24-26. (Periodical Accounts).
+	1824	July	The West Ice was observed on the parallel of Frederikshaab in Longitude 57°W. (Speerschneider 1931).
++	1824	July 24	West Ice at 60°45'N, 57°30'W. (Speerschneider 1931).
+(1)	1825	July 13	Mission ship arrived at Hopedale after meeting no ice on voyage. (Periodical Accounts).
+(3)	1825	August 3	Mission ship had problems with ice on voyage to Nain. (Periodical Accounts).
++	1825	July	West Ice seen in Longitude 56-57°W, north of the parallel of Godthaab. (Speerschneider 1931).
+(2)	1826	July 30	Mission ship arrived at Okak after having had to work its way through 400 miles (644 km) of ice. (Periodical Accounts).
+(3)	1828	August 4	Mission ship arrived at Okak. Anxiety was felt for her due to the immense quantities of ice on the coast during the whole spring. (Periodical Accounts).
+(3)	1829	July 30	Mission ship arrived at Hopedale after being delayed three weeks by ice. (Periodical Accounts).
+(6)	1829	End of August	Immense quantities of drift ice at Okak, which did not leave the coast until this date. (Periodical Accounts).
++	1829	August	Mission ship had to use a new channel between the islands and the coast on voyage to Nain to avoid the ice. (Periodical Accounts).

APPENDIX 1: *REFERENCES TO ICE CONDITIONS ON THE LABRADOR COAST DURING THE NINETEENTH CENTURY*. (Cont'd)

CODE	YEAR	DATE	REMARKS (REFERENCE)
-	1831	Mid-July	Approaches to the older missions blocked by ice. (Periodical Accounts).
+(2)	1831	July 28	Reached Hebron after much trouble with ice. (Periodical Accounts).
-	1831	June	In Latitude 60°N the sea was free of ice west of 58°W. (Speerschneider 1931).
++	1832	June	The West Ice was observed between Latitude 61° and 62°N following the meridian of 58°W. (Speerschneider 1931).
+(5)	1832	July 12	Ice still in the bay at Battle Harbour. (Moss Diary 1832).
-	1832	July 15	Very little ice to be seen from Battle Harbour. (Moss Diary 1832).
+(2)	1832	July 24	Mission ship in ice off Hopedale from July 6 to this date. (Periodical Accounts).
++(4)	1833	August 6	Mission boat arrived at Hopedale and found coast blocked by ice. (Periodical Accounts).
+(4)	1833	August 4	On voyage from Nain to Okak met much drift ice. (Periodical Accounts).
++	1833	June	The edge of the West Ice extended from 64.5°N, 57°W to 66.5°N, 55.5°W. (Speerschneider 1931).
+(4)	1833	June 28	The channel between Wood Island, Strait of Belle Isle, and Labrador froze across. (Maxwell 1887).
++(6)	1833	Mid-July	Pack ice remained in the Strait of Belle Isle to this date. (Maxwell 1887).
++	1834	June	The West Ice was met with a little north of Holsteinsborg on the meridian of 55°W. (Speerschneider 1931).
+(2)	1834	July 24	Mission ship met ice 200 miles (322 km) from the coast. (Periodical Accounts).
++	1835	September	A mass of ice was met with midway between Godthaab and Cumberland Sound. (Speerschneider 1931).
-	1836	July 14	Bay ice at Hopedale broke up - the latest date ever. (Periodical Accounts).
++(4)	1836	August 4	Mission ships reached Hopedale after trouble with ice. (Periodical Accounts).
++	1837	June	The West Ice was sighted 20 miles (32 km) off Svartenhuk and Pröven. (Speerschneider 1931).
++	1837	Mid-November	Immense quantities of drift arrived at Hebron. (Periodical Accounts).

APPENDIX 1: *REFERENCES TO ICE CONDITIONS ON THE LABRADOR COAST DURING THE NINETEENTH CENTURY*. (Cont'd)

CODE	YEAR	DATE	REMARKS (REFERENCE)
-	1838	June	The West Ice was lying in Latitude 63.5°N and Longitude 56-58°W. (Speerschneider 1931).
-	1838	June 10	No ice off Belle Isle. (Talbot 1882).
-	1838	July 28	No ice off Hopedale. (Periodical Accounts).
-/+	1839	July	On the west side of Davis Strait, the sea was free of ice. (Speerschneider 1931).
++(3)	1839	August 2	Hopedale blocked by ice until this date. (Periodical Accounts).
++(4)	1840	August 6	Almost no ice off Hopedale. (Periodical Accounts).
++(4)	1841	August 19	Little or no ice off Okak. (Periodical Accounts).
++	1842	June	The West Ice was observed in Latitude 66°N, Longitude 55°W. (Speerschneider 1931).
-	1843	July 4	Little ice encountered off Hopedale. (Periodical Accounts).
++	1844	July	The edge of the West Ice was 40 miles (64 km) from Greenland at 66°N. (Speerschneider 1931).
+(1)	1844	July 20	Mission ship delayed off Hopedale by ice from July 15 to 20. (Periodical Accounts).
++(3)	1845	August 1	Mission ship forced to turn back by ice while trying to leave Hopedale. (Periodical Accounts).
++	1845	September	The West Ice appeared in Disko Bay. (Speerschneider 1931).
+(1)	1846	July 22	Mission ship arrived at Hopedale after much trouble with ice. (Periodical Accounts).
++(4)	1847	August 11	Mission ship tried to depart Hopedale but driven back by ice, winds and fog. (Periodical Accounts).
-/+	1848	July 8	Mission ships met ice 240 miles (386 km) from Hopedale. (Periodical Accounts).
++(3)	1849	August 2	Little drift ice off Hopedale. (Periodical Accounts).
++	1849	June	On the parallel of Nunarsuit, probably the West Ice was met in Longitude 55°W. (Speerschneider 1931).
+(2)	1850	July 20	Comparatively small quantities of drift ice off Hopedale. (Periodical Accounts).
-(1)	1850	May 25	Ice opened in the Strait of Belle Isle. (Disney and Gifford 1851).

APPENDIX 1: *REFERENCES TO ICE CONDITIONS ON THE LABRADOR COAST DURING THE NINETEENTH CENTURY*. (Cont'd)

CODE	YEAR	DATE	REMARKS (REFERENCE)
+(3)	1852	July 29	Mission ship met first ice off Hopedale. (Periodical Accounts).
-	1852	Late July	Immense masses of drift ice on shore at Nain. (Periodical Accounts).
++(6)	1853	August 25	Little ice on the coast at Hopedale. (Periodical Accounts).
-	1854	Late November	At Nain the sea froze three or four weeks earlier than normal. (Periodical Accounts).
++(4)	1855	August 5	Hopedale blocked by ice. (Periodical Accounts).
++(6)	1856	August 23	Ice blocked the coast at Hopedale from August 5 to 23. (Periodical Accounts).
-	1857	June	The West Ice cannot have reached far towards the east in Davis Strait. (Speerschneider 1931).
-/+	1857	July 7	Mission ship met ice off Hopedale. (Periodical Accounts).
-	1857	July 19	Mission ship reached Hopedale after little trouble with ice. (Periodical Accounts).
+(3)	1858	August 1	Mission ship met ice off Hopedale. (Periodical Accounts).
-	1858	August 8	Mission ships reached Hopedale after little trouble with ice. (Periodical Accounts).
++	1859	July	Between 58°W and 60°W, the edge of the West Ice was trending east-west following the parallel of 63.75°N. (Speerschneider 1931).
++(4)	1859	August 4	Hopedale blocked by ice for several days after this date. (Periodical Accounts).
-	1860	June	The edge of the West Ice was observed some 130 miles (209 km) off Cumberland Sound between 63 and 64°N. (Speerschneider 1931).
++(5)	1860	July 7	Occasional lumps of floe ice in the Strait of Belle Isle. (Packard 1891).
-(1)	1860	July 12	Field ice northeast of Aulezauik Harbour. (Alexander 1861).
++	1861	October 20	Southern Davis Strait full of white ice. (Wakeham 1897).
++	1861	July	Baffin Bay ice blocked the north point of Disko Bay. (Speerschneider 1931).
++(1)	1861	July 17	Reached Hopedale through ice. (Periodical Accounts).

APPENDIX 1: *REFERENCES TO ICE CONDITIONS ON THE LABRADOR COAST DURING THE NINETEENTH CENTURY*. (Cont'd)

CODE	YEAR	DATE	REMARKS (REFERENCE)
+(2)	1862	June 16	The Labrador fleet met a body of ice off Cape Bauld. (Robinson 1889).
++(3)	1862	July 30	Coastal route to Hopedale blocked by ice. (Periodical Accounts).
+++	1863	July	West Ice 20 miles (32 km) offshore north of Holsteinborg. Only a narrow strip of open water between the Storis and the West Ice. (Speerschneider 1931).
+(3)	1863	June 26	The Strait of Belle Isle was clear of ice. (Robinson 1889).
+	1863	June 15	On voyage to Labrador from St. John's much ice encountered. (Rule 1927).
+(3)	1863	July 4	Surrounded by heavy ice off Cape Charles. (Wakeham 1897).
++(3)	1863	July 25	Reached Hopedale through ice. (Periodical Accounts).
++(2)	1863	August 1	Ice off Okak. (Wakeham 1897).
-	1863	Early October	Saw last of the pack ice off Cape Mugford. (Wakeham 1897).
-/+	1864	July	Sea free of ice to 50 miles (81 km) off Cumberland Sound. (Speerschneider 1931).
++(3)	1864	July 31	From the hill at Hopedale the ice could be seen 10 miles (16 km) to the east. (Packard 1891).
+(2)	1864	July 25	May have passed through two streams of ice off Hopedale. (Periodical Accounts).
+(4)	1864	July 1	Ice edge north east of Battle Harbour. (Packard 1891).
+(4)	1864	July 17	Ice off Groswater Bay. (Packard 1891).
+(4)	1864	July 20	Ice cleared at Sloop Harbour. (Packard 1891).
+(4)	1864	Early July	Strait of Belle Isle clear. (Robinson 1889).
-	1865	July 2	The Labrador fleet met little ice to interfere with fishing. (Robinson 1889).
++	1865	July	Off Svartenhuk (65.5°N) the edge of the West Ice was 10 miles (16 km) offshore. (Speerschneider 1931).
+(2)	1865	July 25	Sighted ice off Hopedale. (Periodical Accounts).
++	1866	July	The West Ice was met with at Latitude 62°N and Longitude 60°W. (Speerschneider 1931).

APPENDIX 1: *REFERENCES TO ICE CONDITIONS ON THE LABRADOR COAST DURING THE NINETEENTH CENTURY*. (Cont'd)

CODE	YEAR	DATE	REMARKS (REFERENCE)
-(3)	1866	May 7	Strait of Belle Isle getting clear. (Butler, no date).
-(2)	1867	May 17	Strait of Belle Isle clear of ice. (Butler, no date).
-	1867	June	The West Ice 70 miles (113 km) off Disko Bay. (Speerschneider 1931).
+(1)	1867	July 18	Sighted ice off Hopedale. (Periodical Accounts).
-	1868	July 7	Large quantities of ice on the Labrador coast. (Robinson 1889).
+(5)	1868	July 10	Strait of Belle Isle clear of ice. (Robinson 1889).
++	1868	July	West Ice was 10 miles (16 km) off Svartenhuk (65.5°N). (Speerschneider 1931).
+(6)	1868	July 14	Strait of Belle Isle clear of ice, but a body of ice outside. (Robinson 1889).
+(4)	1870	End of June	Strait of Belle Isle clear of ice. (Robinson 1889).
++(4)	1870	August 14	Hebron did not clear until this date. (Periodical Accounts).
+(4)	1871	End of June	Strait of Belle Isle clear of ice. A large body of ice extending from Grois Island to Belle Isle. (Robinson 1889).
-	1871	July 20	No ice off Hopedale. (Periodical Accounts).
-	1872	June 20	Labrador coast reported blocked by ice. (Robinson 1889).
-	1872	July 18	No ice floes off Hopedale. (Periodical Accounts).
-	1873	June	West ice at 64.5°N, 57.5°W. (Speerschneider 1931).
+(4)	1873	End of June	Strait of Belle Isle clear. (Robinson 1889).
-	1873	July 18	Kirpon blocked by ice until this date. (Robinson 1889).
-	1873	July 18	No ice off Hopedale. (Periodical Accounts).
+(6)	1873	September 2	Drift ice between Hebron and Ramah. (Periodical Accounts).
+(3)	1874	June 20	Strait of Belle Isle clear. (Robinson 1889).
++	1874	June	Only a narrow lane of open water between the Storis and West Ice. (Speerschneider 1931).

APPENDIX 1: *REFERENCES TO ICE CONDITIONS ON THE LABRADOR COAST DURING THE NINETEENTH CENTURY*. (Cont'd)

CODE	YEAR	DATE	REMARKS (REFERENCE)
+(2)	1874	July 17	Ice north of Cape Harrison. (Robinson 1889).
+(2)	1874	July 28	Mission ship reached Hopedale through ice. (Periodical Accounts).
-	1875	May	West Ice at 61°N, 59°W. (Speerschneider 1931).
+(4)	1875	July	Strait of Belle Isle not clear until this month. (Robinson 1889).
++(5)	1875	August 14	Ice moved into Hopedale. (Robinson 1889).
++(6)	1875	August 23	Ice off Hopedale until this date. (Periodical Accounts).
++(6)	1875	August 24	Ice still at Makkovik. (Tanner 1947).
+(1)	1876	June 10	Strait of Belle Isle clear of ice. (Robinson 1889).
+(2)	1876	June 14	Ice off Cape Bauld. (Robinson 1889).
-	1876	June	The coast ice was seen 160 miles (258 km) off Sukkertoppen. (Speerschneider 1931).
+(3)	1876	July 31	Drift ice off Hopedale. (Periodical Accounts).
-(1)	1878	May 25	Strait of Belle Isle clear. (Robinson 1889).
-	1878	June 30	Labrador fleet able to reach harbour stations. (Robinson 1889).
++	1878	July	The West Ice was observed 30 miles (48 km) off Holsteinborg. (Speerschneider 1931).
+(1)	1879	June 10	Strait of Belle Isle clear. (Robinson 1889).
-	1879	July 15	Body of ice moved down the Labrador coast on this date. (Robinson 1889).
+(2)	1879	July 20	Great quantities of ice off Hopedale. (Periodical Accounts).
+	1880	May 27	Ice 150 miles (242 km) southeast of Battle Harbour. (Robinson 1889).
-	1880	July 23	Drift ice bordered the coast off Hopedale for 40 miles (64 km) seaward. (Periodical Accounts).
+(2)	1880	July 31	At Hebron the coast was blocked by ice until this date. (Maxwell 1887).
+(4)	1880	June 28	Strait of Belle Isle clear of ice. (Robinson 1889).
+(5)	1880	July 25	A body of ice east of Belle Isle. (Robinson 1889).

APPENDIX 1: *REFERENCES TO ICE CONDITIONS ON THE LABRADOR COAST DURING THE NINETEENTH CENTURY*. (Cont'd)

CODE	YEAR	DATE	REMARKS (REFERENCE)
+	1880	September 8	Pack ice in southern Davis Strait. (Wakeham 1897).
-	1881	-	Bad ice year off East Greenland. Little ice off Labrador. (Smith 1928).
+(3)	1881	June 20	Pack ice reported in the Strait of Belle Isle. (Robinson 1889).
+(3)	1882	June 18	Strait of Belle Isle clear. (Robinson 1889).
+(2)	1883	June 16	Strait of Belle Isle clear. (Robinson 1889).
-(6)	1884	Mid-April	Strait of Belle Isle clear of ice. (Robinson 1889).
+(3)	1884	August 3	Drift ice had prevented the Mission ship from reaching Hopedale before this date. (Periodical Accounts).
++	1884	August	The edge of the West Ice was 40 miles (64 km) offshore from Holsteinborg. (Speerschneider 1931).
+(2)	1885	June 15	Strait of Belle Isle clear of ice. (Robinson 1889).
-	1885	October	Pack ice in southern Davis Strait. (Wakeham 1897).
-(2)	1886	May 17	Strait of Belle Isle clear of ice. (Robinson 1889).
-(1)	1886	June 10	No ice at Cape Harrison. (Robinson 1889).
(4)	1887	June 30	Strait of Belle Isle clear of ice. (Robinson 1889).
-	1887	July 28	Ice from Ragged Island north. (Robinson 1889).
+	1887	July	The West Ice was lying close inshore at Disko Bay. (Speerschneider 1931).
+(3)	1887	August 10	Pack ice left Nain. (Robinson 1889).
++	1888	July	The West Ice was observed 10 miles (16 km) off Disko Bay. (Speerschneider 1931).
+(4)	1888	August 4	Mission ship arrived Hopedale August 4 through ice. (Periodical Accounts).
++	1889	July	The edge of the West Ice was 40 miles (64 km) offshore at Holsteinborg. (Speerschneider 1931).
+(1)	1891	July 17	Coast clear to Hopedale. (Cilley 1898).
-	1893	July 30	Mission ship arrived Hopedale. No ice on coast. (Periodical Accounts).
-	1896	July 23	No field ice outside the Strait of Belle Isle. (Wakeham 1897).

APPENDIX 1: *REFERENCES TO ICE CONDITIONS ON THE LABRADOR COAST DURING THE NINETEENTH CENTURY.* (Cont'd)

CODE	YEAR	DATE	REMARKS (REFERENCE)
++	1896	October 30	Pack ice well down Labrador coast. (Wakeham 1897).
+(1)	1897	June 7	Light ice off Battle Harbour. (Wakeham 1897).
-	1897	June 29	Ice left Strait of Belle Isle. (Wakeham 1897).
+(2)	1897	July 30	Scattered ice east of Cape Chudleigh. (Wakeham 1897).
+(4)	1897	Early December	Arctic pack north of Belle Isle. (Wakeham 1897).
++(7)	1899	August 19	Ice still near Makkovik. (Periodical Accounts).

HISTORICAL SOIL MOISTURE IN THE PRAIRIE PROVINCES: A TEMPORAL AND SPATIAL ANALYSIS

Roger B. Street and D.W. McNichol[1]

INTRODUCTION

The Prairie Provinces periodically experience long dry spells as a normal characteristic of their climate. The economy and society are, in general, adjusted to withstand or compensate for the inconveniences and losses of income associated with these occurrences, knowing that problems will be alleviated in a few months. Occasionally, however, serious dislocations to agriculture and other sensitive water resource activities are the result of unusually severe and prolonged dry periods. These fall into the generally conceived definition of drought: a condition requiring evidence of damage to the regional economy and social structure (Hoyt 1938; Palmer 1965; Glantz 1979).

A meteorological drought is a severe dry spell expressed as a long-term lack of precipitation over a region, or as a water shortage or deficit within the soil. Human activity and the environment may or may not be affected; therefore, this is a qualified form of drought. However, meteorological drought is almost inevitably a precursor of the "true" drought which has a socio-economic impact. Meteorological drought may be studied through an examination of precipitation, evapotranspiration and upper-air circulation. The quantity and quality of these data vary over time, and therefore, place constraints - both in time and space - on the analysis.

To systematically study the complexities of drought, which may be considered in terms of timing, extent, duration and severity, it is necessary to first develop a suitable expression of meteorological drought. This will provide a sound platform for further research. Soil moisture is considered a prime parameter. However, soil moisture is not directly measured on a routine basis. Required is a means of estimating soil moisture that is sufficiently simple to make effective use of available long-term climatological records, but accurate enough to resolve information at the necessary time-scale. A continuous climatic water balance in which temperature and precipitation are the main climatological input parameters to a soil-moisture budgeting procedure will provide the required temporal and spatial definition within the limits of available data. A soil-moisture budgeting procedure which considers the aforementioned constraints has been developed as part of an Atmospheric Environment Service program, which is intended to document the nature of drought - particularly in those areas of Western Canada most severely affected.

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The continuous climatological water balance procedure uses daily values of temperature, precipitation, soil texture and other physical data to calculate evapotranspiration, soil moisture and related moisture status parameters at grid points throughout the study area at 10-day intervals. The soil-moisture status at each grid point is assessed from two discrete strata: an upper layer extending from the surface to plow-depth (approximately 15 cm) holding up to 12.5% of the full moisture capacity; and a deeper underlying zone retaining 87.5% of the water when at theoretical maximum storage (field capacity). Each layer supplies moisture for evapotranspiration or receives percolated water from precipitation.

The study area encompasses that region bounded by the 92nd and 120th meridians and from the United States border to the 60th parallel including the Prairie Provinces and adjacent regions of Ontario and British Columbia. More than 170 climatological stations located within this area have provided information on the major dry periods for the years 1925-1980. To overcome difficulties associated with discontinuous records and unequal distribution of stations, the climatic data have been projected onto an equal-area spatial grid by means of a polynomial objective analysis. For this study, a rectangular grid-point base developed for hydrometeorology (den Hartog and Ferguson 1978) and used by Agriculture Canada was selected. It has a coordinate system where points are spaced at one degree of longitude intervals such that each point is centred within a 10,000 sq. km rectangle.

For each grid point, components of the climatic water balance are computed every 10 days continuously from the beginning of the data set or from 1925. The grid size was selected because of the compatibility with other required data for drought studies: soil texture, agricultural yield and area in cultivation, and streamflow measurements. It was also chosen to aid in distinguishing local effects on drought severity and extent caused by areal differences in precipitation and evaporative demand. The number of grid points for which values may be computed increases progressively with time: 1925-30 produces 93 point values; 1931-40, 157 values; 1941-59, 207 values; and 1960-80, 220 values. This reflects improvements in the network. The model considers snowmelt, interception, and infiltration in order to specify detail on the timing, spatial characteristics intensity and duration of severe dry spells (or other applications).

This paper is concerned with the variability in both time and space of meteorological drought as depicted by analysis of estimated soil moisture. Two methods of examining the complexities of drought are presented: time-series analyses at specific grid points; and a spatial analysis of decade mean soil moisture. All analyses have been done with respect to long-term mean soil-moisture values that were calculated for each grid point and each 10-day period within the year.

TIME-SERIES ANALYSIS

Individual time-series plots of percent of normal soil moisture averaged over three 10-day periods were prepared for three discrete locations in the Canadian Prairie Provinces (Figure 1). The grid points selected represent areas in the vicinity of Brandon, Manitoba; Gravelbourg, Saskatchewan; and Rycroft, Alberta. These areas were chosen on the basis of a preliminary analysis identifying them as typical of the soil moisture behaviour characteristic of the three individually distinct larger areas of southern Manitoba, southwestern Saskatchewan and central Alberta. In addition, these three areas have been associated historically with drought events. During the following discussion, each of the time-series analysis will be examined for trends and implications insofar as local meteorological drought is concerned.

(1) Brandon, Manitoba

This time-series analysis shows an extended period of soil moisture values generally near or below normal from late 1928 throughout most of the thirties and the first years of the forties. The only years during this period in which some recovery was apparent was during the spring of 1935, and the spring of 1937 through to the summer of 1938. After the fall of 1938, when values reached a maximum negative departure from normal, a slow recovery of soil moisture towards more normal values is depicted, with above normal values reached during the summer of 1941.

Of particular interest for the Brandon time-series plot are extreme above-normal values during the late summer and fall of 1959, followed by generally below-normal values from the

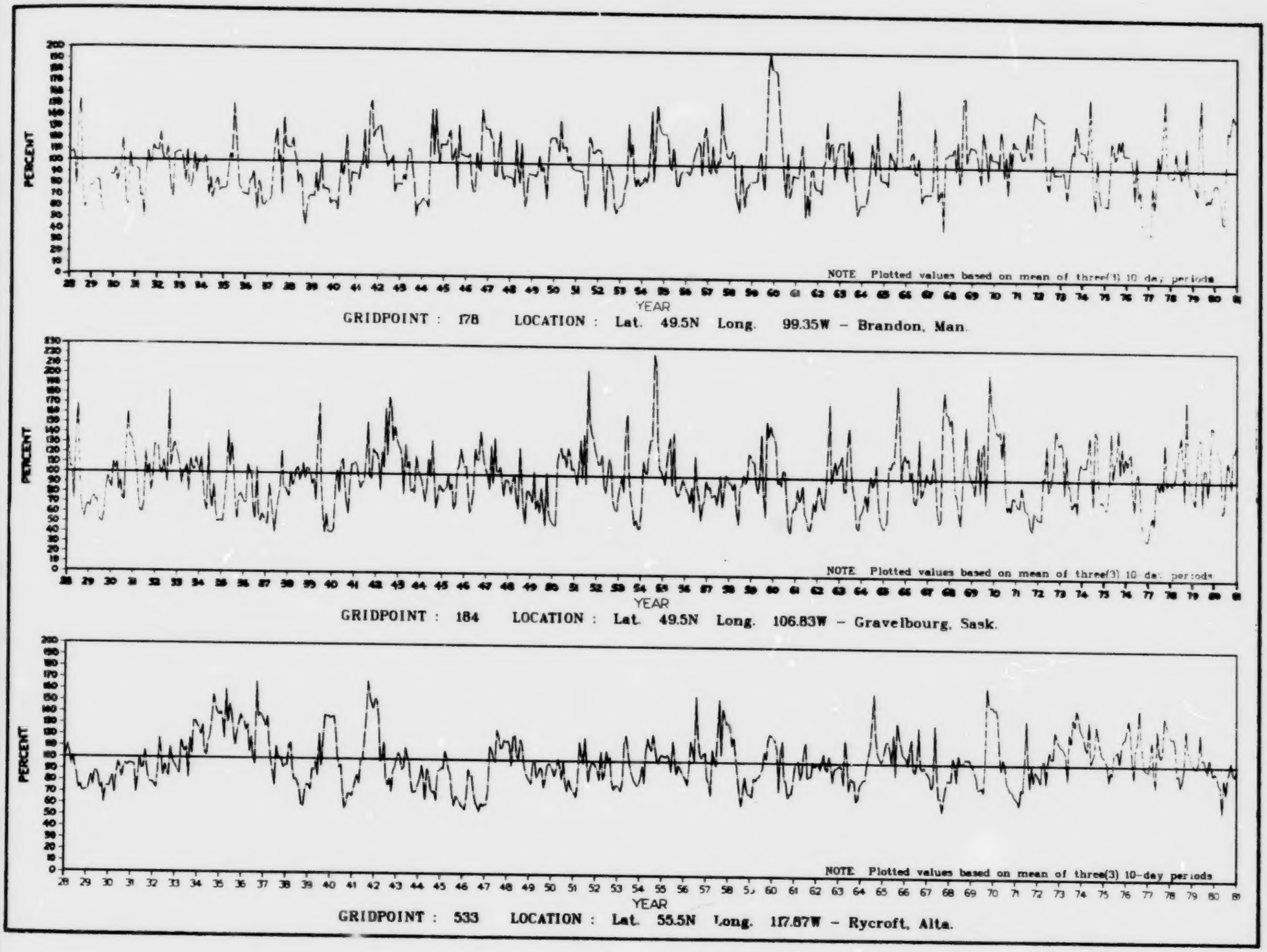


FIGURE 1: *Time-series analysis of soil moisture (sum of upper and lower layer) as a percent of long-term mean values averaged over three 10-day periods.*

spring of 1960 through to the spring of 1962 (1961 drought). In addition, the greatest negative departure from normal occurs during the fall of 1976, which coincides with the winter drought of 1976-1977.

The tendency for soil moisture values to gradually increase or decrease slowly over an extended period of time is evident in this, as well as the other, analyses. This tendency gives the time-series analyses a wave-like appearance which is particularly apparent during the thirties and during the period from the spring of 1977 through to the spring of 1980. However, this gradual change is not always present as is apparent from the Brandon analysis for the period 1959-62.

(2) Gravelbourg, Saskatchewan

Apparently the Gravelbourg area did not suffer from as extended a period of below-normal soil-moisture values during the thirties as did Brandon. Generally, soil moisture was near or above normal from 1931 through to the fall of 1934. However, soil-moisture values dropped below normal in 1934 and, except for a short period in 1935 and 1939, remained near or below normal normal through to the summer of 1941.

Some noteworthy events depicted by the Gravelbourg analysis include the dry periods from the fall of 1947 through to the spring of 1950 and from the summer of 1955 to the fall of 1958. Also, the period from the summer of 1970 through to the spring of 1972 represents a significant departure from normal over a significant period of time (i.e., drought). The largest negative departures from normal soil-moisture values occur during the winter months of 1939-40 and 1976-77.

(3) Rycroft, Alberta

Our analysis for the Rycroft area shows below-normal values beginning during the summer of 1928 and reaching a maximum negative departure from normal during the winter of 1929-30. Recovery of soil-moisture values following this winter was slow but steady, above-normal values being reached following the summer of 1933. Soil-moisture values remained above normal during the mid-thirties, before decreasing again to below normal values in 1938 and 1939.

Of particular interest, are the generally below-normal soil-moisture values near the end of the Second World War (1943-47), and covering periods such as 1949-54 and 1960-64, when values were generally at or below normal except for a one or two 30-day period when they were above normal. Remarkable also is the long period from 1972 to 1979 when soil-moisture values were predominately above normal, and the fact that there is no evidence of the 1976-77 winter drought.

A measure of drought severity is the cumulative deviation from normal of soil moisture values over a given period of time (Yevjevich 1967). A cursory examination of the time-series curves reveals several years during which the soil-moisture deficit could be defined as more severe. These periods are noted in Table 1 for the three locations previously analyzed.

TABLE 1: *PERIODS OF SEVERE SOIL-MOISTURE DEFICIT AT BRANDON, GRAVELBOURG AND RYCROFT (1928-1981).*

LOCATION	PERIODS OF SEVERE SOIL-MOISTURE DEFICIT
Brandon, Manitoba	summer 1928 - summer 1930
	summer 1935 - spring 1937
	spring 1938 - spring 1941
	fall 1942 - summer 1944
	spring 1976 - spring 1977
	summer 1979 - summer 1980
Gravelbourg, Saskatchewan	fall 1928 - fall 1930
	summer 1939 - summer 1941
	summer 1955 - summer 1958
	fall 1960 - summer 1962
	summer 1970 - spring 1972
	spring 1976 - summer 1977
Rycroft, Alberta	summer 1928 - spring 1933
	summer 1942 - spring 1947

SPATIAL ANALYSIS OF DECADE MEAN SOIL MOISTURE

Decade mean soil-moisture values as percept of long-term means (Figure 2) have been plotted and analyzed for period 18 (10-day period ending on Julian calendar date 180, i.e. June 29) for the decades 1931-40, 1941-50, 1951-60, 1961-70 and 1971-80 (Figures 3-7,

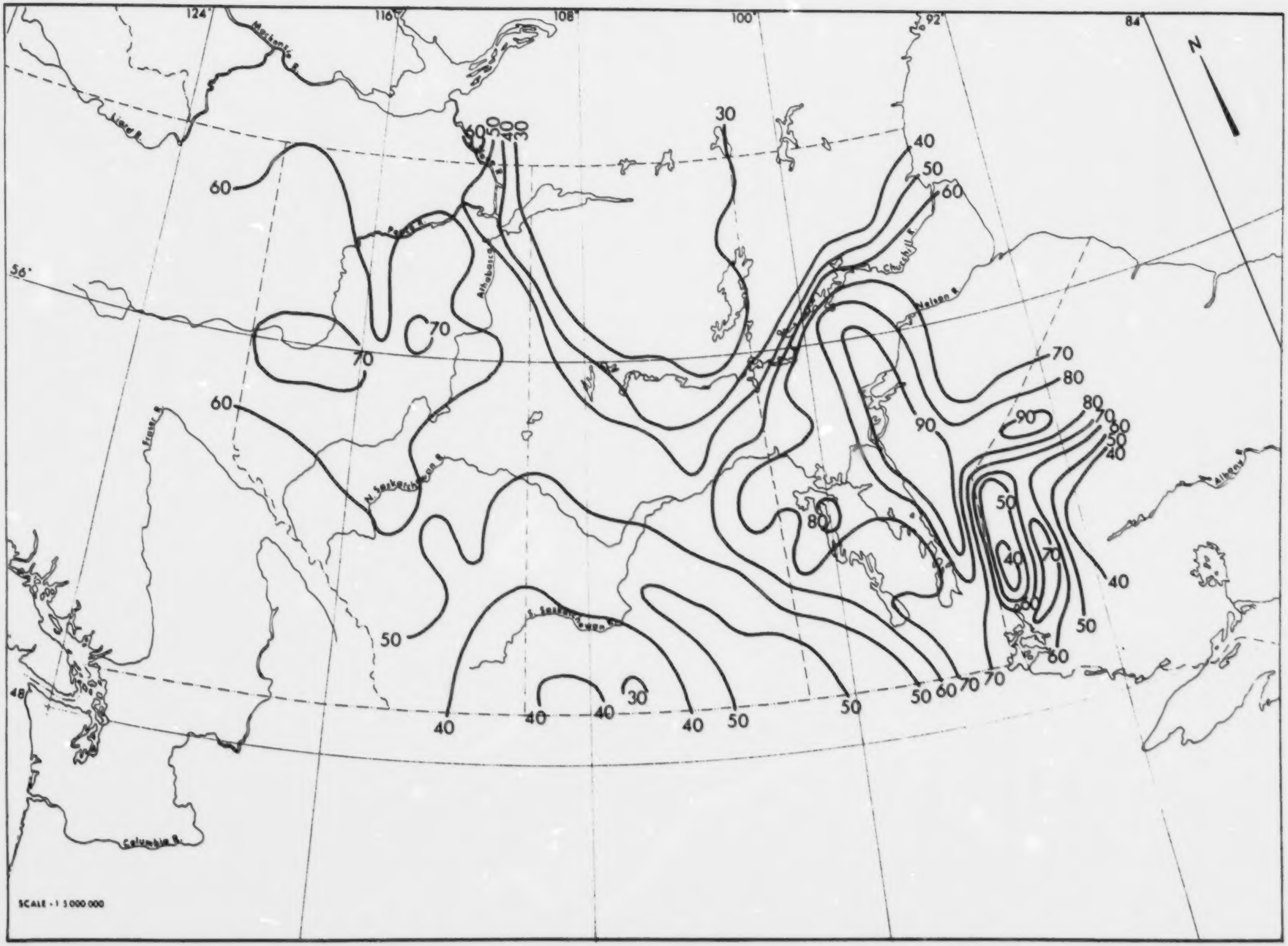
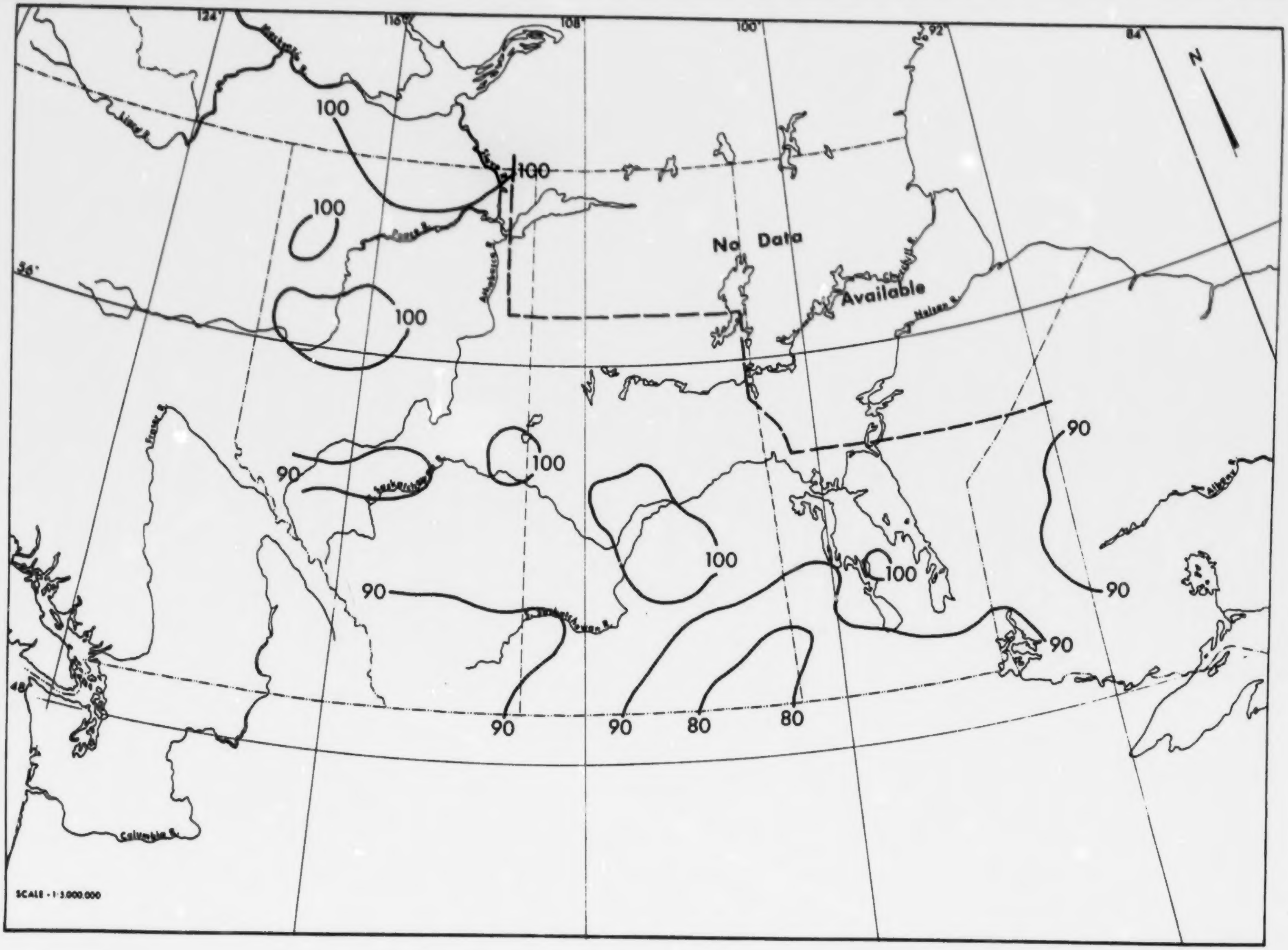

124°
116°
108°
100°
92°
84°
56°
48°
N
Mackenzie R.
Liard R.
Peace R.
Athabasca R.
Churchill R.
Nelson R.
N. Saskatchewan R.
S. Saskatchewan R.
Fraser R.
Columbia R.
Albany R.
SCALE - 1 5 000 000
30
40
50
60
70
80
90

FIGURE 2: *Long-term mean soil moisture values (sum of lower and upper layer) for the 10-day period ending on Julian calendar day 180.*


124°
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92°
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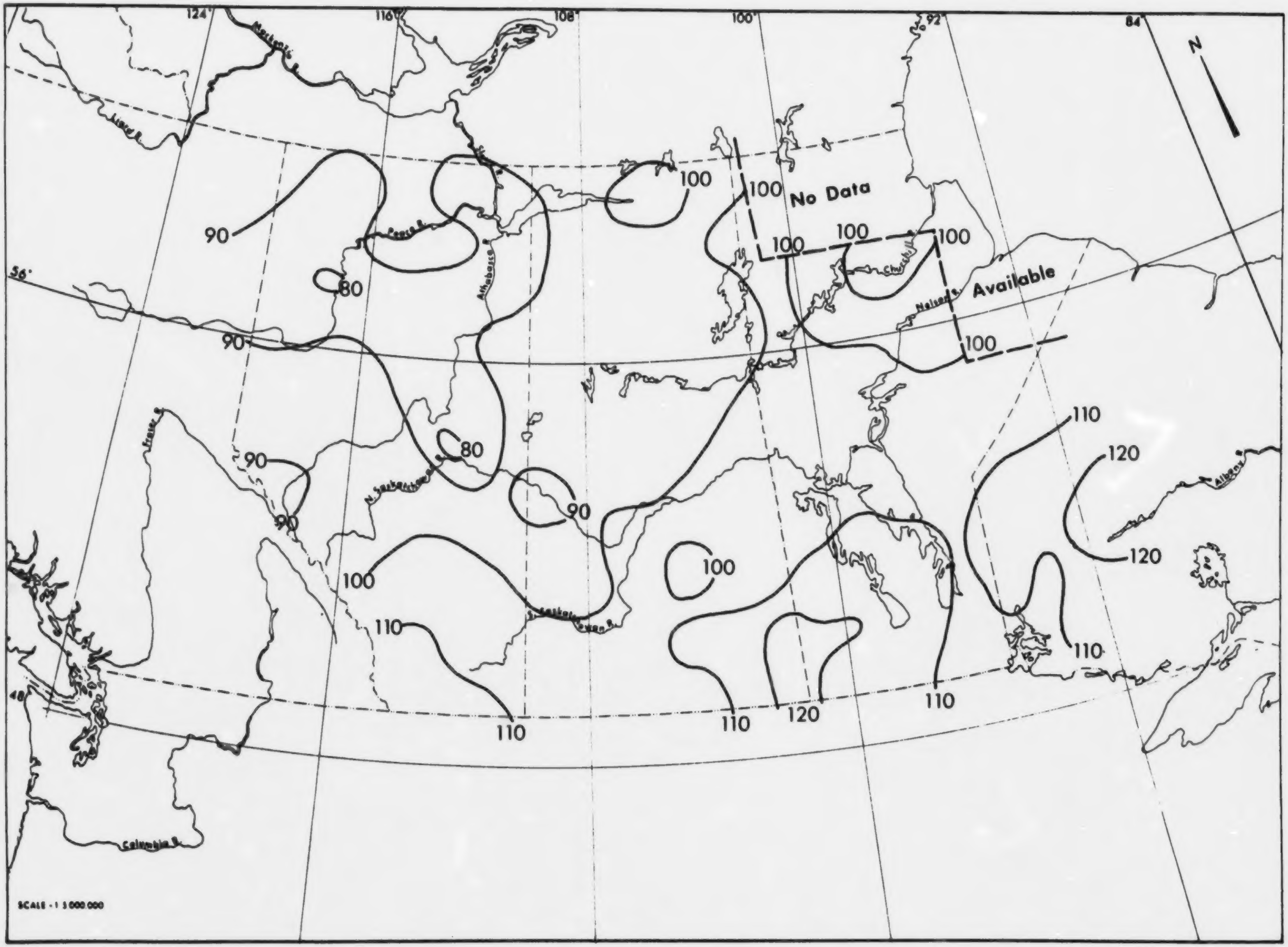
56°
48°
N
No Data
Available
100
100
100
100
100
100
100
90
90
90
90
90
90
90
80
80
Mackenzie R.
Liard R.
Peace R.
Athabasca R.
Slave R.
Churchill R.
Nelson R.
Saskatchewan R.
Albany R.
Fraser R.
Columbia R.
SCALE - 1:3,000,000

FIGURE 3: *Mean soil moisture (sum of lower and upper layer) during the 1931-40 decade as a percent of long-term normal values for the 10-day period ending on Julian calendar 180.*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Peace R.
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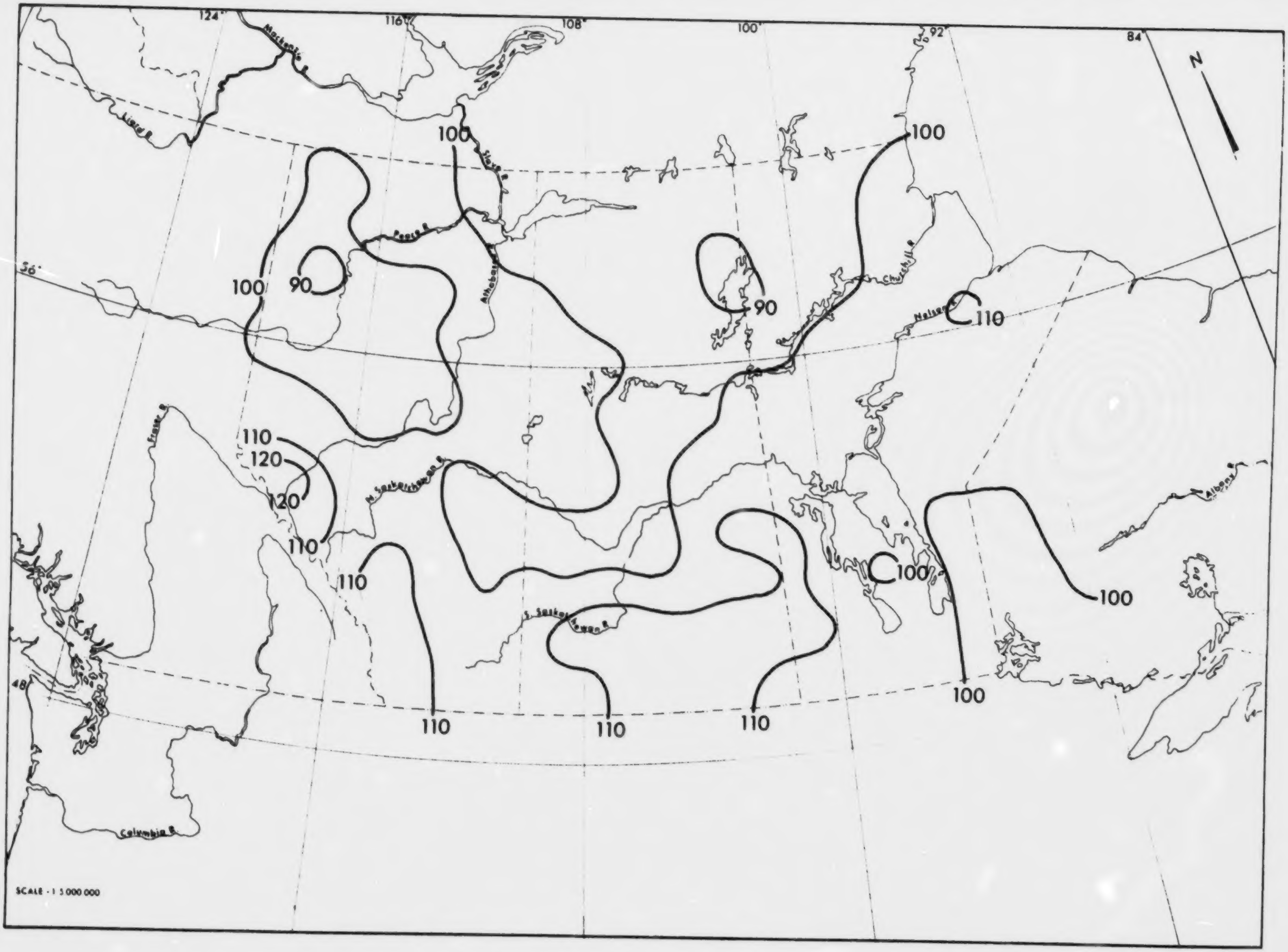
N. Saskatchewan R.
S. Saskatchewan R.
Churchill
Nelson R.
Albany R.
Fraser R.
Columbia R.
No Data Available
90
80
90
90
90
80
90
100
100
100
100
100
100
100
100
110
110
110
110
110
110
110
120
120
120

FIGURE 4: *Mean soil moisture (sum of lower and upper layer) during the 1941-50 decade as a percent of long-term normal values for the 10-day period ending on Julian calendar day 180.*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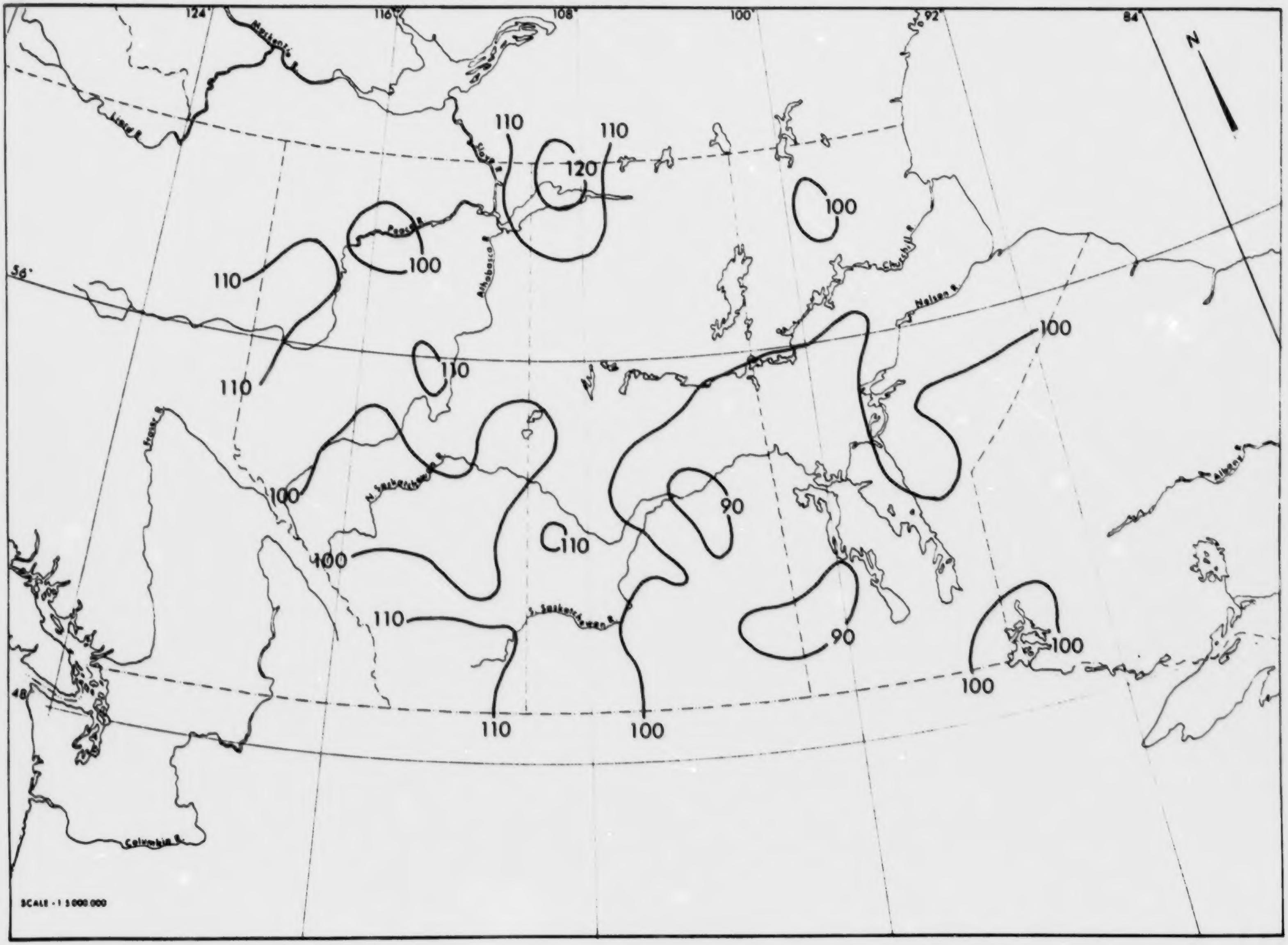
N
Mackenzie R.
Liard R.
Slave R.
Peace R.
Athabasca R.
Churchill R.
Nelson R.
Fraser R.
N. Saskatchewan R.
S. Saskatchewan R.
Columbia R.
Albany R.
100
100
100
90
90
110
110
120
120
110
110
110
110
110
100
100
100
110
SCALE 1:5 000 000

FIGURE 5: *Mean soil moisture (sum of lower and upper layer) during the 1951-60 decade as a percent of long-term normal values for the 10-day period ending on Julian calendar day 180.*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Mackenzie R.
Liard R.
Peace R.
Slave R.
Athabasca R.
Churchill R.
Nelson R.
Albany R.
Fraser R.
N. Saskatchewan R.
S. Saskatchewan R.
Columbia R.
110
120
110
100
110
100
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110
100
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100
90
100
110
90
100
100
110
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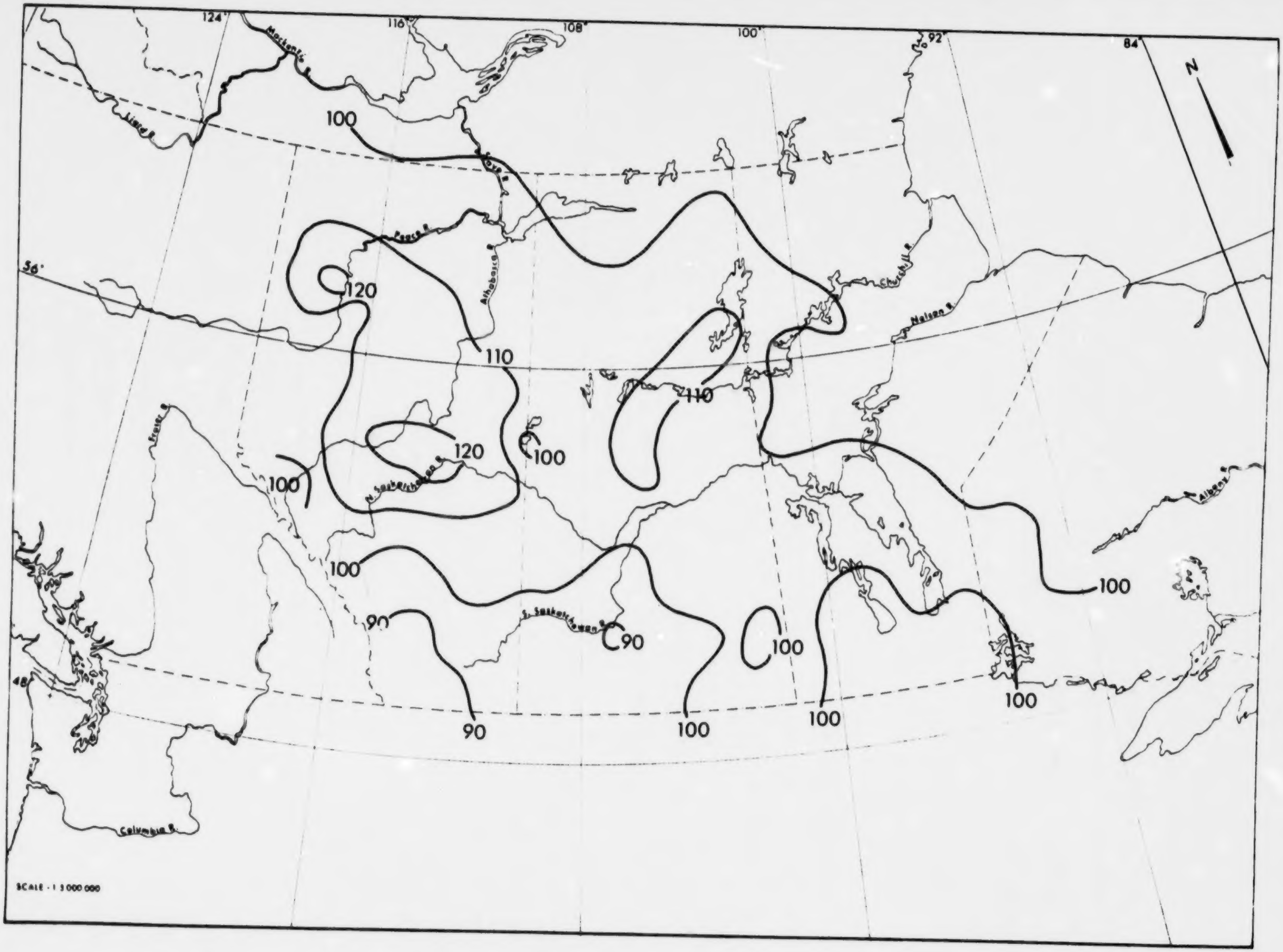
SCALE 1:5 000 000

FIGURE 6: *Mean soil moisture (sum of lower and upper layer) during the 1961-70 decade as a percent of long-term normal values for the 10-day period ending on Julian calendar day 180.*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84°
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56°
48°
Mackenzie R.
Liard R.
Slave R.
Peace R.
Athabasca R.
Churchill R.
Nelson R.
Albany R.
Fraser R.
N. Saskatchewan R.
S. Saskatchewan R.
Columbia R.
100
120
110
120
100
100
110
100
100
90
90
90
100
100
100
100
100
SCALE 1:5 000 000

FIGURE 7: *Mean soil moisture (sum of lower and upper layer) during the 1971-80 decade as a percent of long-term normal values for the 10-day period ending on Julian calendar day 180.*

respectively). Period 18 was chosen for this particular analysis because the amount of moisture available then is felt to be critical for potential agriculture crop production. The long-term mean soil-moisture analysis reflects the variation in water-holding capacity of the different soils, as well as the distinct climate regions of the Prairie Provinces.

These decade analyses reveal the spatial, as well as temporal, variations of soil moisture with respect to the long-term normals. The 1931-40 decade analysis shows that, except for small pockets such as those in central Saskatchewan and the Peace River region, soil moisture values for this time of year during the thirties were generally below normal. In particular, the area of southeastern Saskatchewan and southwestern Manitoba shows the largest departure from normal with values less than 80% of normal analyzed. Generally below-normal soil-moisture values for period 18 continued during the decades 1941-50 and 1951-60 in central and northern Alberta and Saskatchewan. However, throughout Manitoba and southern Alberta and Saskatchewan, soil-moisture values for period 18 were above normal during these same decades.

Soil-moisture values for period 18 during the 1961-70 decade in southern Manitoba, the eastern half of central and southern Saskatchewan, and central Alberta were generally below normal. On the other hand, the northern parts of the Prairie Provinces and southern Alberta and western Saskatchewan experienced decade mean values of soil moisture that were above normal. This, to some degree, was a reversal of the northwest-southeast soil-moisture gradient established in the previous two decades. As was the case during the thirties, southeastern Saskatchewan and southwestern Manitoba was analyzed as having the lowest decade mean soil-moisture values. During this decade, however, an additional area east of Prince Albert, Saskatchewan also experienced mean soil-moisture values for period 18 that were less than 90% of long-term normals.

The 1971-80 decade analysis reveals that soil-moisture values for period 18 remained generally above normal throughout central and northern Alberta and Saskatchewan. The areas in the vicinity of Peace River and northeast of Edmonton, Alberta, in particular, experienced decade means which were in excess of 120% of long-term normal soil-moisture values. In the southern Prairie Provinces, a westward shift in the soil-moisture minimum values from southeastern Saskatchewan to southern Alberta and southwestern Saskatchewan is apparent. Period 18 mean decade soil-moisture values in southern Manitoba remained near, to slightly below, normal during 1971-80 - as they had in the previous decade.

CONCLUSION

As a starting point in the systematic understanding of drought-onset and alleviation, a climatological study such as this is of value despite its limited scope, since it reveals some of the basic characteristics of soil-moisture availability. Meteorological factors are intimately involved in drought occurrence, but the relationships are far from simple. A considerable task lies ahead in achieving a deeper understanding of soil moisture and, therefore, drought characteristics.

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SOME ASPECTS OF THE CALIBRATION OF EARLY CANADIAN TEMPERATURE RECORDS IN THE HUDSON'S BAY COMPANY ARCHIVES: A CASE STUDY FOR THE SUMMER SEASON, EASTERN HUDSON/JAMES BAY, 1814 to 1821.

C. Wilson[1]

INTRODUCTION

While regular temperature observations were made at a number of Hudson's Bay Company Posts during the latter part of the eighteenth century into the nineteenth century, the interpretation of these early *Registers of the Thermometer* in the Company's archives in terms of the modern Canadian temperature series presents a number of difficulties. Besides such matters as the accuracy of the early instruments, the exact location and nature of early observing sites and discrepancies in times of observation, there is the difference brought about by direct exposure of the early thermometer to the local thermal environment -- usually in a north window, on a north wall or in open shade. This served to link the temperature series more closely to the immediate site in question than is generally the case with the modern free-standing Stevenson screen. Unfortunately, either the observers often omitted to record information concerning their specific instruments, observing sites and practices, or such material has not survived. These early temperature series represent a large investment of time, effort and frequently devotion on the part of the observers, but unless calibration problems can be resolved - at least to within acceptable confidence limits - their value in climatic change studies is restricted.

As part of a continuing study of climatic fluctuations along the east coast of Hudson/James Bay during the summer season in the nineteenth century, based on the Hudson's Bay Company archives, an attempt has been made to calibrate the temperature records kept at Whale River (Great Whale), Big River (Fort George) and Eastmain from 1814 to 1821 (Figure 1). This coastal region provides an excellent laboratory. A modern first-order weather station has been in operation at Great Whale since 1925, supplying both fixed-hour and daily (maximum and minimum) temperature data. Climatological stations at Fort George, from 1915

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[1] P.O. Box 887, Station B, Ottawa, Ontario, K1P 5P9. This study was carried out under contract to the Atmospheric Environment Service (AES), Downsview, Ontario.

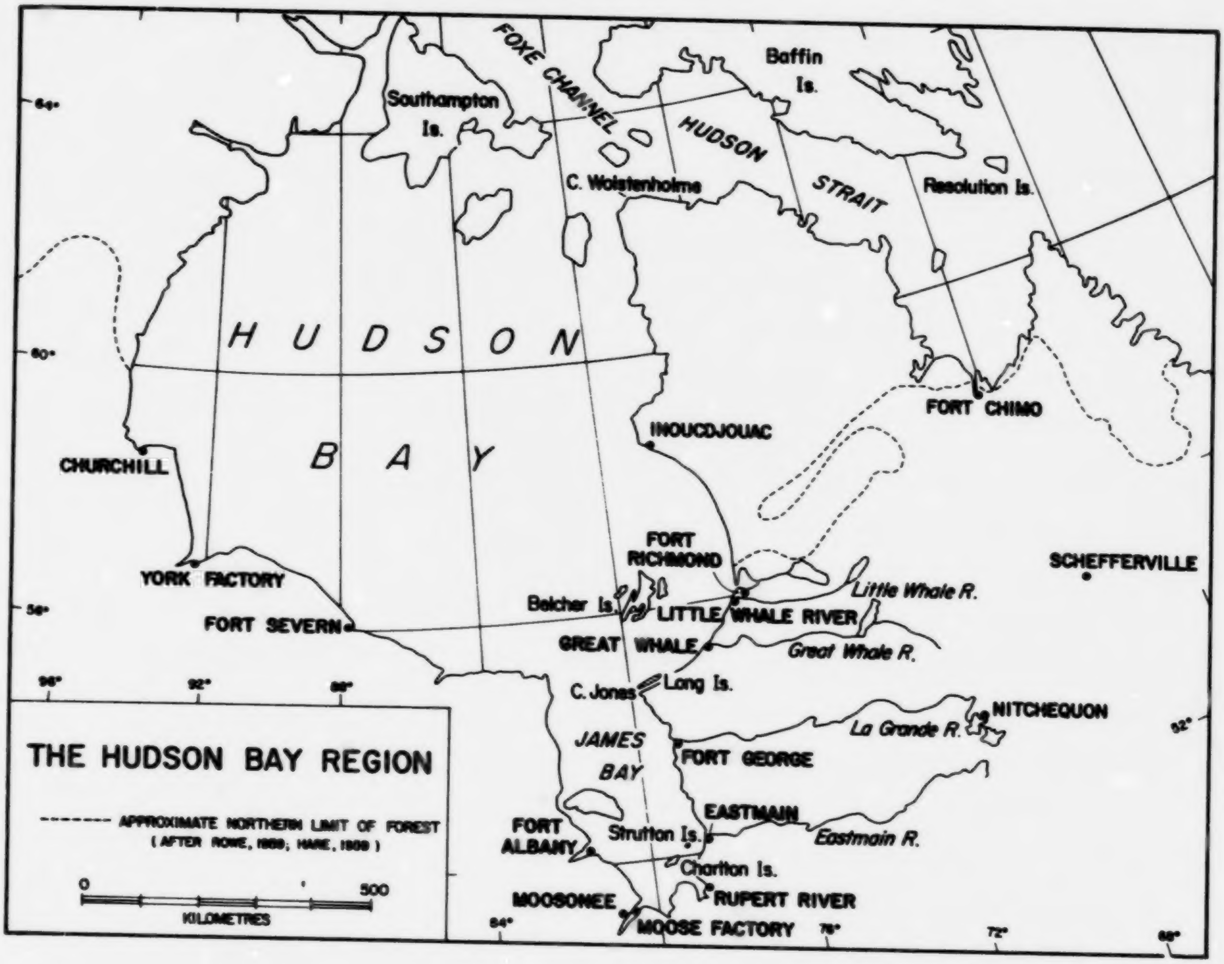
Baffin Is.
FOXE CHANNEL
Southampton Is.
64°
HUDSON STRAIT
C. Wolstenholme
Resolution Is.
60°
HUDSON BAY
FORT CHIMO
INOUCDJOUAC
CHURCHILL
FORT RICHMOND
SCHEFFERVILLE
YORK FACTORY
Little Whale R.
56°
Belcher Is.
LITTLE WHALE RIVER
FORT SEVERN
GREAT WHALE
Great Whale R.
96°
92°
88°
C. Jones
Long Is.
NITCHEQUON
La Grande R.
52°
JAMES BAY
FORT GEORGE
THE HUDSON BAY REGION
APPROXIMATE NORTHERN LIMIT OF FOREST (AFTER ROWE, 1959; HARE, 1959)
0
500
KILOMETRES
FORT ALBANY
Strutton Is.
EASTMAIN
Eastmain R.
Charlton Is.
RUPERT RIVER
MOOSONEE
MOOSE FACTORY
84°
76°
72°
68°

FIGURE 1: *General map of the Hudson Bay region. Note: in 1966, the settlement of Great Whale became known as Poste-de-la-Baleine, and Great Whale River as Grande rivière de la Baleine. More recently, the Inuit name Kuujjuaraapik has been introduced. The name Great Whale is retained in this study for continuity and simplicity. Similarly, the more familiar Cape Jones has been preferred in this context over the official Pointe Louis-XIV.*

to 1969, and at Eastmain from 1960 provide daily temperature readings. Personal field experience offered supplementary data and useful firsthand knowledge concerning the character of the regional climate.

APPROACH

Judgement concerning the value of an historical temperature series implies some knowledge of the degree of accuracy and homogeneity in the corresponding modern series. Otherwise we may be asking more of the early record than the modern data are providing. The problem has therefore been expressed as follows:

(1) What are the probable limits of the errors we are dealing with in the historical data?
(2) Are they acceptable in the light of the probable limits of error in the modern record?

The calibration has been approached in three ways: physically — an examination of the systematic temperature differences which might arise as a result of changes in site, instruments, their exposure and observing practices, given the distinctive qualities of the northern surface conditions and the regional and local weather; statistically — an application and extension of current Canadian Quality Control procedures, and the fitting of a simple regression model; historically — the reconstruction of the early sites and social context, and of the meteorological instrumentation and procedures accepted at the time, based primarily on the archives of the Hudson's Bay Company and the Royal Society, London. Historical and physical considerations provide the basic assumptions upon which the statistical solutions rest. A serious attempt has been made to set confidence limits, although these must remain best estimates. However, I hope that the various aspects of the calibration have been made explicit enough to allow those interested to accept, reject or amend the assumptions and conclusions at each stage, and hence reconsider these limits if they see fit. Given the very partial nature of the surviving evidence, an ever-present danger is that of circular argument. Historical assumptions are based, as far as possible, on the convergence of evidence. This article summarizes the study and conclusions; the detailed evidence and argument, and a full list of references, are presented in a contract report (Wilson 1981).

DATA

Historical data coverage for Whale River, Big River and Eastmain, May to October, is shown in Figure 2, together with times of observation as indicated on the Registers. "Fixed-hour" temperature readings were taken daily, usually in the early morning, near midday and in the later afternoon/early evening. At Whale River and Big River, daily maximum and minimum temperatures were also recorded. The keeping of the weather records was designated as the duty of the Clerk.

The synoptic station at Great Whale offers the most complete set of modern weather observations for this region. The modern data base selected for the study consisted of daily and hourly readings for Great Whale, from May to October 1957 to 1976, together with daily values for Fort George and Eastmain within the same period, and monthly mean daily maximum, minimum and extreme temperatures for all three weather stations over the whole period of record. Both the historical and modern temperature series were recorded in degrees Fahrenheit, and these units were retained in the calibration. To conform with modern Canadian usage, the results in the text and tables are given in degrees Celsius; there are, however, exceptions in the section on instruments, and in those Figures which deal directly with the data.

ENVIRONMENTAL FACTORS

During the summer season, the nature of the arctic/subarctic terrain, the presence of ice and/or icy waters in the Bay, and the dominating influence of regional and local surface wind direction on the radiation climate of this coast are of direct interest in evaluation of the historical weather data, and in assessment of the homogeneity of the modern record.

Terrain

The coastal region forms part of the Precambrian Shield, and consists of low rounded granite/gneiss hills and promontories, with a series of sand/clay marine terraces and beach ridges, which extend up the valleys. North of Cape Jones, in the vicinity of Great Whale, the bedrock outcrops to form a low dissected plateau, 100 to 200 m high, rising abruptly from the narrow coastal and riverine terraces (cf. Figure 3). South of Cape Jones, the edge

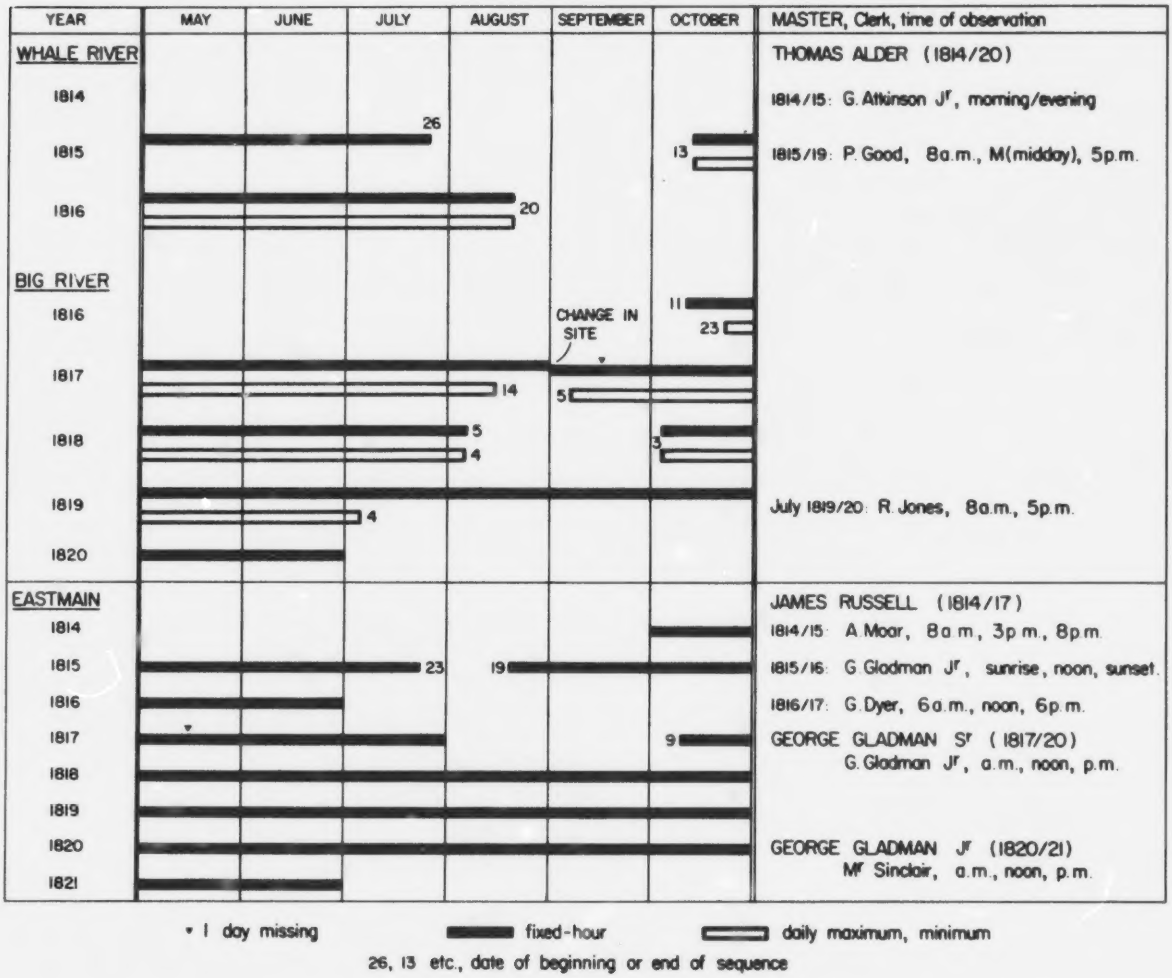

FIGURE 2: *Whale River, Big River, Eastmain, 1814 to 1821: temperature data coverage, observing officers, time of observation.*

of the plateau runs inland to the southeast, and the coastlands in the vicinity of Fort George and Eastmain consist of low, rolling plains of glacial and postglacial deposits, broken through occasionally by outcrops of bedrock. Coastal hills do not rise much above 30 to 45 m, and the slope inland is gentle (cf. Figures 4 and 5). Near Fort George, the coast is indented and festooned with small low islands. Towards Eastmain, the islands die out and the coast becomes smoother and more open.

Lying between Latitudes 52 and 56°N, this zone extends at present from the Subarctic to the seasonally fluctuating Arctic borders. Many trees have their northern limits just south of Cape Jones. To the north, in the district of Great Whale, is the forest-tundra — a mosaic of diverse tundra and open lichen-woodland sites. Trees on the more exposed sites are stunted, and on the coastal plateau they are generally confined to sheltered valleys and hollows. Here, white spruce is present at the coast, black spruce and tamarack just inland, with alder, willow and dwarf birch. To the south, near Fort George, lichen-woodland generally offers a better forest cover, and includes some jack pine and balsam fir. Farther south, as far as Eastmain, the forest becomes richer again in type and growth, and the lichen floor is often replaced by shrubs. A significant change south of Fort George is the increasing proportion of humid and wet sites, characterized by extensive areas of bog and swamp (including sphagnum and other mosses, sedges, black spruce and tamarack).

This northern coastal landscape offers observing sites whose surfaces, *when dry*, have very different physical properties from the recommended short-grass cover usually adopted in more temperate regions. Three major components of the floor of the coastal and riverine terraces in the vicinity of the three Posts are bare sand and the non-transpiring lichens and mosses (surfaces which dry out quickly once the drying power of the air increases and/or the sun breaks through). All have very low thermal capacity and conductivity, so that they heat quickly in sunshine and cool rapidly when the heat source is cut off. By the same token heat transfer below the surface is severely limited. With the suppression of the evaporative and ground heat fluxes, most of the available energy is converted into sensible heat, and under favourable conditions creates warm, dry enclaves. Under certain atmospheric conditions and with low sun, the reflected and diffuse short-wave radiation associated with the dry sand and lichens is considerably greater than with short grass. When ground cover is removed or disturbed by building and traffic, it regenerates slowly, and the drier sites tend to degenerate into a local desert of bare sand with isolated clumps of tall, coarse grass.

Coastal terraces are generally free from snow by the last week in May. In autumn, snow can be expected to lie from the last half of October. The rivers, at the coast, are usually clear of ice from mid- or late May, and completely frozen over again by about late November - early December.

Hudson/James Bay

Break-up and melt of ice in the Bay take place from late May into July and August, with the last remnants of ice usually in the south or southwest. In general, almost all of the Bay is still open at the end of October. By mid-July, uninterrupted open water can normally be expected along the east coast from southern James Bay to the north of Inoucdjouac, with the area between Cape Jones and Great Whale as the last stronghold of the ice in this region (Sowden and Geddes, to be published). However, large differences occur in the timing and pattern of break-up from one year to the next. Final clearing along this coast has been completed as early as mid-June, and as late as the third week in August.

Water-surface temperature is closely related to the timing and pattern of the particular break-up season (cf. Wendland and Bryson 1969). When clearing is early, the water warms rapidly near the ice/water margins; but when ice lingers well into August, the heating potential has been greatly reduced. Estimated average offshore surface temperatures in July range from about 5°C near Great Whale to 11°C near Eastmain; corresponding values for August, September and October are 8 to 13°C, 7 to 11°C and 3 to 6°C, respectively (Danielson 1969).

Although the pattern and timing of break-up and melt of the Bay ice can be critical in colouring the seasonal climate along the coast, clearly the relationship between Bay surface conditions and coastal weather conditions involves complex feed-back, dependent as both sets are on regional and local surface wind direction. However, with respect to instrument calibration, it is useful to note the thermostatic effect of the ice on the monthly frequency of daily maximum, minimum and hourly temperatures (see, for example, Figure 11).

Surface Winds

During May and early June, this region normally has some of its finest weather under spring anticyclones from the north, but from mid-June onward, it is generally dominated by a series of depressions from the southwest and west. Thus, with onshore westerlies prevailing along this coast, the influence of the Bay looms large. At Great Whale from May to October, 1962 to 1971, hourly winds were from the Bay 55% of the time, and close to 63% when only daylight hours were considered; 6% of the hours were calm. Modern hourly weather data are not available for Fort George or Eastmain. The following analysis is for Great Whale.

Winds from the Bay (SW-N)

(i) The winds from the SW quadrant are mostly associated with the warm sector of the depressions. From May into July and August, air temperature is lowered and relative humidity increased in passing over this fetch of ice and cold water, to produce cool days with fog, drizzle and low stratus cloud, or cold, dark, blustery weather with heavy precipitation. Noon incoming solar radiation can be as little as 157 Wm^{-2}. Where fog and low cloud are related to a local or regional drift of air during otherwise clear, anticyclonic conditions, the sun's disc or small flecks of blue sky may become visible for an hour or two during the middle of the day. By early September, however, the air-water temperature differential approaches zero.

(ii) With winds from the cold NW quadrant, the influence of the Bay in spring depends on the distribution and amount of open water, and the origin of the northerly flow. With the ice intact, these winds may bring expectionally clear, dry air and large amounts of incoming solar radiation. Although air temperature may be close to 0°C at sites exposed to wind, out of the wind with a southerly aspect, air temperature may be 5 to 10°C warmer for sand or lichen sites. Where cold air is modified by passage over relatively warmer open water, stratocumulus or fog and stratus can shroud the coast - with noon incoming solar radiation as low as 295 Wm^{-2}. Through the summer, as the ice clears and the water warms, flow from this quadrant produces a shallow but effective stratocumulus cover over the coastal zone; this may thin or open up locally for an hour or two in the middle of the day. This sector also comprises the sea breeze component (WNW-N), when cool air with rafts of stratocumulus drifts in over the coast. This cloud tends to dissipate over the heated sand

and lichens of the terraces and to reform over the hills. Where exposed to this light cool breeze, steep temperature gradients are formed between the strongly heated sand and lichen surfaces and the air at screen level; such surfaces may be as much as 25 to 30°C warmer than the air. In late autumn, the comparatively warm surface of the water can trigger extensive cumulus formations and spectacular snow squalls in the cold northwesterly flow from the Arctic, separated by brilliant shafts of sunlight.

Winds from the Land (NNE-SSW)

(i) The cool NE quadrant. Winds from this sector are relatively light and most frequently associated with sunny weather at this season, although cirrus streaks are rarely totally absent. Atmospheric transmissivity is high, especially in May and early June (~0.80), and incoming solar radiation received at the ground approaches maximum values — for example, a noon flux as great as 926 Wm^{-2}. Again these are conditions where microclimatic differences arising from surface type, slope, aspect and shelter are clearly defined.

(ii) The warm SE quadrant. Although winds from the land generally bring clearer weather, those from the SE quadrant include the warm regional advection, frequently heralding or associated with the warm sector of a depression. Skies are rarely totally free of cirrus, and on occasions the approaching depression may bring an overcast of middle and high cloud and some precipitation. These airstreams are not only more humid but have a higher turbidity. The timing and frequency of these cases of warm advection in spring and early summer form an important component in the seasonal climate. When the regional pressure gradient is well-defined, these southerly winds can deteriorate into a persistent, dessicating gale, with drifting and blowing sand and heavy low-level haze — the wind speed possibly accelerated near the surface by the alignment of the coastal topography and the steep local temperature gradient between heated land surfaces and ice/cold waters of the Bay. At such times, sustained hourly wind speeds of 12 m/s or more, gusting to over 15 or 20 m/s, are not unusual, associated with daytime screen temperatures from 21 to 30°C and relative humidity at 15 to 35%. Such searing conditions may last one or two days. With atmospheric transmissivity as low as 0.63, the daily receipt of incoming solar radiation may be some 20% less than for NE flow, however the amount of diffuse radiation can be 30% greater. With a slack regional pressure gradient, light winds from this sector can bring sunny, if slightly hazy, warm to very warm weather from spring to early autumn. Near midday, change to a light NW Bay breeze may bring a marked drop in temperature, until this dies down again later in the afternoon.

To sum up, the warm season climate at Great Whale has two dominant modes. Firstly a subarctic maritime mode characterized by cold advection reflecting the Bay conditions. Radiation input is small and limited to exchange of diffuse and long wave; the cloud blanket, dampness and moderate wind speeds minimize vertical and horizontal temperature differences near the ground. Radiative and thermal properties tend to be similar for all moistened surfaces. However, the effect of shelter from Bay winds may not always be negligible. Secondly, a continental mode associated with effectively clear or partly cloudy, dry conditions and, in general, offshore winds. At these latitudes, large amounts of incoming solar energy are received at the ground in spring and summer; differential radiative exchanges, given the mosaic of subarctic surface types and sites, maximize both vertical and horizontal temperature differences. At times of regional or local drift of clear, cold air, such differences tend to be reinforced. Extreme changes of weather can occur very rapidly, often within the hour, and many subarctic surfaces respond quickly. Thus the distinction between the two modes can be quite sharply defined, along this coast. Normally, the first mode is predominant, but the frequency of the second colours the seasonal climate and its variability.

With respect to the influence of offshore waters at Fort George and Eastmain, the fetch at these two sites, although greatly reduced, remains more than 160 km. Winds from the Bay include directions from SSW to NNW at Fort George and SW to NW at Eastmain. However, ice in James Bay normally breaks up 2 to 4 weeks earlier than farther north, and surface waters can be expected to be from 2 to 5°C higher, July to September. In addition, these two locations are 2 and 3° further south in latitude, so that under sunny conditions air temperature levels at this season would be expected to be higher. In fact, a marked climatic gradient occurs in the vicinity of Cape Jones. This is reflected in the northern limits of a number of species of trees, and in the occurrence of coastal tundra to the north. Nevertheless, a comparison of daily weather observations and monthly summaries, for selected years for Great Whale, Fort George and Eastmain, suggests that the differences are of intensity rather than kind, and that the coastal region under study essentially falls under similar climatic controls.

CALIBRATION OF THE HISTORICAL TEMPERATURE DATA: PHYSICAL CONDITIONS

In the absence of direct evidence concerning the type of instruments, their exposure and observing practices at these three Hudson's Bay Company Posts, it has been necessary to rely on the close collaboration which existed between the Company and the Royal Society with respect to meteorological observation and experiment in the second half of the eighteenth into the early nineteenth centuries. Dating from 1768, when two visiting scientists, William Wales and Joseph Dymond made and recorded meteorological observations at Fort Prince of Wales (Churchill)[1], under the auspices and precise instruction of the Society, a tradition of careful meteorological observations was established on the west coast of Hudson Bay. This was fostered by such Company officers as Thomas Hutchins, Andrew Graham and William Falconer at York Factory, Albany Fort and Severn House, who were keen observers. It was a period when the Royal Society was interested in the design and calibration of thermometers, and in regulating, observing and recording procedures, and the Hudson's Bay Company was actively involved.

At Eastmain, on the east side of the Bay, there is only one meteorological journal for this early period prior to 1814; but the Bay community was closely knit. As well as direct contact between Masters and officers, especially at Shiptime, and a certain interchange of personnel between Posts, there was a large internal correspondence. There is also a sense of continuity in time between generations, in the case of one or two distinguished Bay families.

Furthermore, the weather observing program initiated by the Hudson's Bay Company in 1814 was given a high priority. It formed part of a study to assess the food-producing potential of the region, with a view to cutting down on the great expense of supplying the Bay Posts with European food, at a time of increasing financial and economic stress and social unrest in Europe and North America, and keen competition from the North West Company. Most likely there was consultation with the Royal Society concerning instruments and observing procedure. The historical timing was such that the study was not completed, but regular weather observations were continued until the Hudson's Bay Company amalgamated with the North West Company in 1821.

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[1] Ed. note: See the paper by T.F. Ball that follows in this volume.

Modern weather station histories for Great Whale, Fort George and Eastmain are also incomplete in this respect, particularly for the period before 1946 at Great Whale, and 1956 at Fort George. For Eastmain, information is sparse. Therefore, I have had to assume that instrumentation, exposure and procedure were those required by the Canadian Meteorological Service at the time.

Sites of Posts and Modern Weather Stations

Great Whale - Whale River

The settlement at Great Whale (Figure 3) occupies a series of many terraces and beach ridges, which form a point at the north side of the river estuary. The lower reaches of the river valley are deeply entrenched in the granite and fluviomarine deposits. The site is treeless and open from the southwest to north-northwest to the full fetch of the Bay.

There have been five changes in site since the modern weather station was set up in 1925. The location of the first two observing sites from 1925 to 1957, near the edge of the terrace overlooking the river (Figure 3A), was similar to that from 1814 to 1816. Until 1954, the underlying sand was almost undisturbed, covered by a mat of low vegetation in which lichens and mosses were mixed in varying proportion with small flowering plants, grasses and dwarf shrubs. Removal of the ground cover and construction of the Mid-Canada Line Base, from 1954 to 1957, brought about desertification and urbanization of the environment (Figure 3B). In 1957, the weather station was moved inland about 0.8 km to the north on the uppermost terrace, to serve the airport. Subsequently there were two further changes of instrument site down the western slope of the terrace. For the six months following the major shift inland, daily maximum and minimum temperature observations were continued at the previous site at the river bank. An analysis of these differences showed clearly the positive effect of the large artificial heat input on minimum temperatures during the snow-cover season. These measurements were not continued during the summer, to

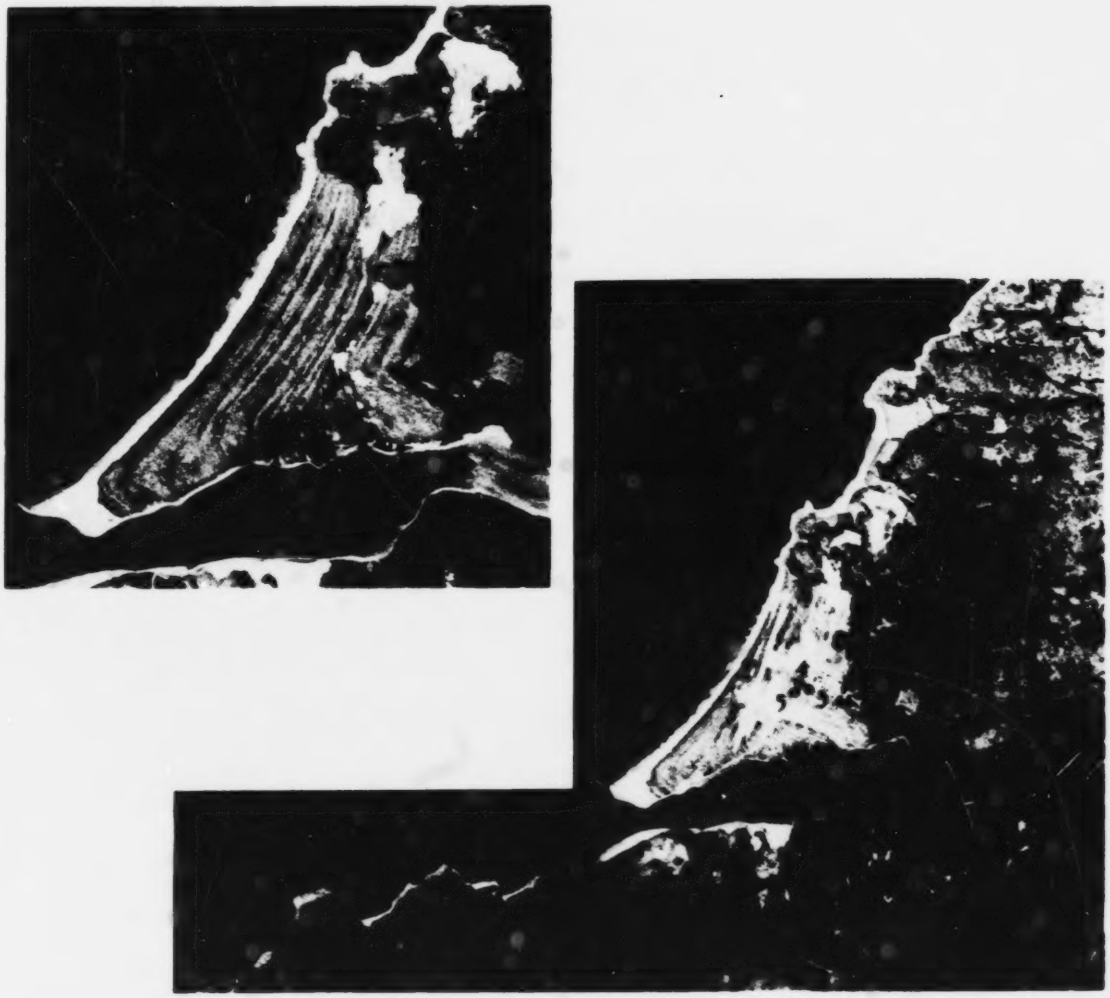

FIGURE 3: *Great Whale, environmental changes and location of instrument sites. A. Airphoto (A14176-86) June 28, 1954 (1:42,000). Site 1, 1814-16, 1925-52: Site 2, 1952-57. B. Airphoto (A23865-225) August 24, 1974 (1:64,000). Site 3, 1957-61: Site 4, 1961-70; Site 5, 1970 --. These aerial photographs © (1954, 1974) Her Majesty the Queen in Right of Canada, reproduced with permission of Energy, Mines and Resources Canada.*

test the effects on screen temperature of the large expanse of bare sand and of the change in surface roughness. In addition, the artificial heat sources are present during most of the warm season.

A careful study of the implications of these environmental changes, incorporating field data for Great Whale and elsewhere, and frequencies of key weather situations, suggests that a significant increase in temperature might occur in extremely warm months and during abnormally cold months dominated by anticyclonic conditions. In these cases, the abnormal degree of warmth might be overestimated and the degree of cold underestimated compared with earlier years. Table 1 summarizes the estimated limits of such differences. Absolute differences in the hourly values would probably be more conservative. In the case of the 1958-76 averages of monthly mean daily temperature, any increase would probably be less than 0.3°C from May to August, and close to zero in September and October. With respect to site, the 1814-1816 records for Whale River have been accepted as homogeneous with those for 1925-1957.

TABLE 1: *GREAT WHALE: ESTIMATED DIFFERENCES IN SCREEN TEMPERATURE BETWEEN THE INLAND SITES (SINCE 1957) AND THE NORTH BANK OF THE RIVER (1925-57), DURING THE WARM SEASON.*

A. Estimated Upper Limits

Mean daily differences over the month	
Mean daily maximum temperature	+1.5°C
Mean daily minimum temperature	+1.0°C
Mean daily temperature	+1.0°C
Extreme daily temperature over the month	
Extreme maximum	+3.0°C
Extreme minimum	+2.0°C

B. Estimated Variability of Daily Differences

95% of cases, maximum temperature	±5.0°C
minimum temperatures	±4.0°C

C. Extreme Months, Differences in Mean Daily Temperature

MEAN DIFFERENCES °C	M	J	J	A	S	O
Warm months	≤ +1.0	≤ +1.0	≤ +1.0	≤ +1.0	≤ +0.5	≤ +0.3
Cold months:						
(i) cyclonic	< +0.5	< +0.5	< +0.5	< +0.5	±0.0	< -0.3
(ii) anticyclonic	< +1.0	< +1.0	< +1.0	< +1.0	< ±0.3	±0.0

Fort George - Big River

Fort George is located near the north shore of Governor's Island in the estuary of the La Grande River, about 4.5 km due east of James Bay (Figure 4). The settlement is situated in a clearing in the lichen woodland, open to the river on the north through east; in the mid 1950s the maximum depth of the clearing was about 0.5 km. Once the lichen mat has been disturbed the surface is one of loose sand with isolated clumps of tall, coarse grass and weeds.

The modern climatological station located near the river bank appears to have had two instrument sites. The first operated by the Hudson's Bay Company seems to have been similar to that from 1817 to 1820; the second lay some 250 m to the southeast, and little temperature difference would be anticipated. The smaller forest clearing in the historical period (diameter: height ~ 4:1 or 5:1) would suggest higher maximum temperatures under quiet, sunny conditions and to a lesser degree higher minimum temperatures on clear, quiet nights. However, under these weather conditions, the effect of the smaller clearing acts in the same sense as the modern disturbance of the surface and increase in artificial heat input. From 1816 to 1817, the Post was situated across the river on the north bank. This site presents a rather different set of conditions, with its opposing aspect and immediate hinterland of wooded hills. In this case there was possibly a relative underestimate of temperature during warm southerly advection in spring and summer, but to what extent this may have been compensated by enhanced radiation or "softening" of northerly flow in sunny weather cannot be ascertained.

Eastmain

Eastmain is situated on the south shore of Eastmain River, about 4.8 km east of James Bay (Figure 5). The settlement occupies three or four small clearings along the river bank, open to the north. The terrain is rather humid, including extensive areas of bog and swamp, and stands of closed forest.

Between 1960 and 1976, the climatological station was located about 120 m to the southwest of the Hudson's Bay Post and removed from habitation. The Stevenson screen was sited on organic terrain, over tall, coarse grass, sedges and milkweed, with probably a moss

FIGURE 4: *Fort George, location of instrument sites. Airphotos (A15277-68) June 23, 1956 (1:60,000). Site 1, 1816-17; Site 2, 1817-20, 1915-33; Site 3, 1933-69. This aerial photograph © (1956) Her Majesty the Queen in Right of Canada, reproduced with permission of Energy, Mines and Resources Canada.*

FIGURE 5: *Eastmain, location of instrument sites. Airphotos (A15256-56 and A15259-15) June 17, 18, 1956 (1:60,000). Site 1, 1814-21; Site 2, 1960 --. These aerial photographs © (1956) Her Majesty the Queen in Right of Canada, reproduced with permission of Energy, Mines and Resources Canada.*

ground layer. The site of the Post from 1814 to 1821, similar to that today, was just above the surrounding swamp, and drier. At that time, it was the principal settlement on the east coast. It included several heated buildings, and was enclosed by a system of stockades and fences (Figure 6). In general, the historical site would probably have been warmer.

Instruments, Historical and Modern

Eastmain, 1814 to 1821

At Eastmain, the thermometer graduated in degrees Fahrenheit, was probably made about 1805 or 1806. There is evidence to suggest that it was mercury rather than spirit, and hermetically sealed. Only fixed-hour readings were made. Although the search for a standard instrument was not undertaken by the Royal Society until 1830, by the beginning of the nineteenth century increasing accuracy had been achieved, and mercury thermometers were being recognized as more reliable (Middleton 1966).

It is difficult to gauge the order of instrument error. An indication of the calibration in the lower range is provided by the morning temperatures when the mercury is said to be frozen. Taking into consideration Hutchins' (1783) and Cavendish's (1783) work, the error at this point may have been between minus 1 and 2°F (0.6 and 1.0°C). Around 32°F, there is with rare exception consistency between the temperature and other weather information related to freeze and thaw (cf. Potter 1969). At the upper limit, there were two readings of 92°F: for example, on May 24, 1818, Gladman writes in the Journal "... the hottest day I ever experienced in this country. Thermometer stood some hours at 92°F in the coldest shade" (HBC, B59/a/99). Under similar clear skies and light southerly flow, respective readings at Big River were both 90°F. The extreme maximum temperature at Eastmain, 1960 to 1976 (broken), is 93°F. Considering the difference in the historical and modern instrument exposure, this can only be taken as a rough check on the performance of the instrument per se.

Two sources of error for mercury thermometers at this period were, firstly, the slow rise in the zero with time (positive error) caused by the contraction of the glass bulb on aging, and not then recognized by the Society; secondly, the nature of the scale, frequently of small 5-degree intervals and indicated only on the mount — readings were recorded to the

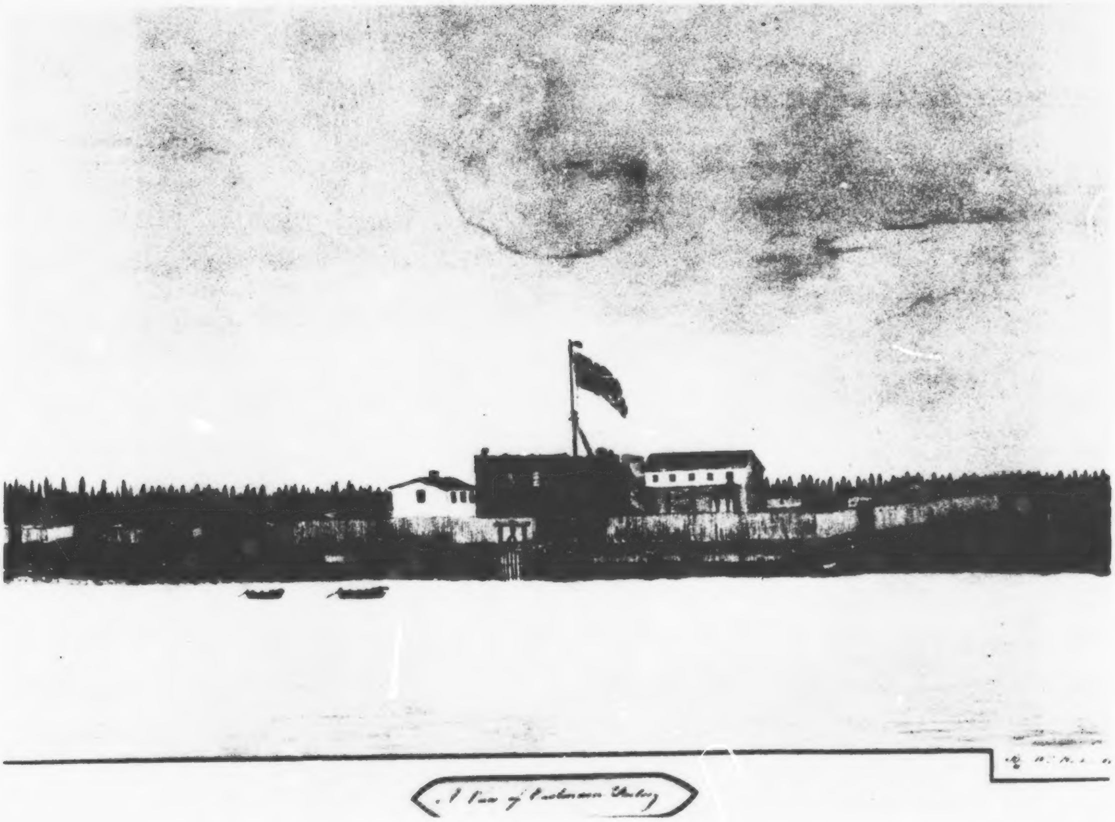
A View of Eastmain Factory

FIGURE 6: *A view of Eastmain Factory, by William Richards. Watercolour (20" x 13") painted in October, 1807. (Reproduced with kind permission of the Hudson's Bay Company.).*

nearest whole degree. In addition, response time may have been more rapid than with modern liquid-in-glass thermometers, which could have resulted in some positive error in the presence of the observer and a greater sensitivity to natural small-scale temperature fluctuations, especially near midday.

Whale River, Big River, 1814 to 1820

At these two Posts, a single instrument was used to record daily maximum and minimum temperature and fixed-hour readings. When Whale River was evacuated in 1816 in favour of Big River, the thermometer was transferred. Evidence strongly suggests that it was an early Type-Six self-registering maximum, minimum thermometer (Six 1782), favoured by the Royal Society until the middle of the century. The active fluid is spirit, the mercury column acting only as an indicator. Compared with the modern Type-Six, the bulb was exceptionally large, 0.79 cm in diameter and 40.64 cm long (Figure 7), and the stem long. Considering the larger expansion coefficient of the spirit and the mass of spirit involved, its response time was probably greater than for the mercury instruments of the period, but not unlike that of the modern standard liquid-in-glass thermometers. One great advantage was that the daily extreme temperatures were obtained with minimal interference from the observer's presence. Readings, in degrees Fahrenheit, were to the nearest whole degree.

A careful calibration of a Type-Six against a mercury Standard at Greenwich, from 1841 to 1843 (Royal Observatory Greenwich 1843 to 1845), indicated that the error in the daily maximum and minimum readings from May to October was minimal around 32°F, but consistently positive above freezing, increasing with increasing temperature to as much as 4.4°F (2.4°C) above 80°F (26.7°C). In the few cases below freezing, there was a tendency for a small negative error. The three-year monthly averages suggest a systematic instrument error of the order of +2 to +3°F (1.1 to 1.7°C) for temperatures > 70°F (21.1°C), and +1°F (0.6°C) below 70°F. This is in keeping with the view that with spirit, the lag coefficient is a function of temperature (Middleton and Spilhaus 1953). Other possibilities for error include: (1) the spirit wets the glass and can eventually pass between the glass and the mercury indicator; again, (2) if the temperature falls rapidly, liquid may remain on the walls of the tube; (3) on exposure to light, the spirit tends to diminish in volume with age; (4) the spirit column is more easily broken, and a break less easily seen. On the

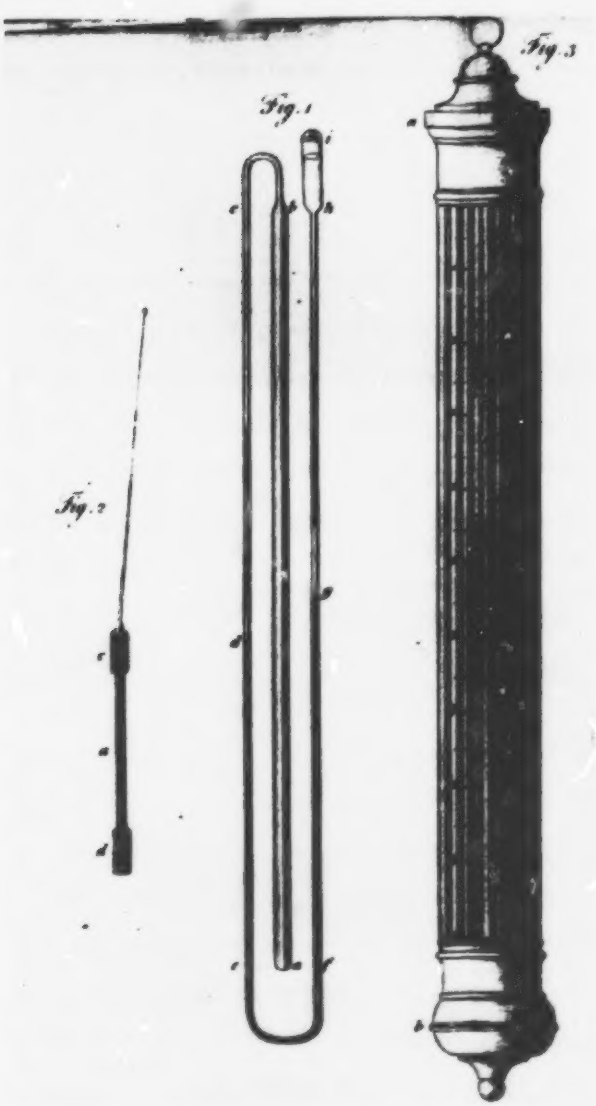

FIGURE 7: *James Six's (1782, Figures 1-3) self-registering maximum, minimum thermometer. Reproduced with kind permission of the Royal Society, London. Figure 1: a-b, bulb; Figure 2: enlargement of an index. Figure 3: thermometer with mount and scales.*

other hand, the problem of the rise in the zero through aging of the glass is less serious than for mercury.

Looking at extremes of temperature as a rough indicator of the performance of the instrument, at the upper limit, 92°F was recorded at Whale River on July 14, 1815 in a strong SW gale (HBC, B372/a/2); at Eastmain, 89°F was registered with SW winds and clear skies. More recently, on June 7, 1974, the screen maximum was 87°F at Great Whale, with winds S to SSW at 11.6 m/s, gusting to 17.4. While the extreme at Whale River may have been high under these conditions, it remains compatible with the modern 38-year extreme of 93°F. At Big River, the highest temperature recorded was 90°F on May 24, 1818 and again on July 27, 1819 (HBC, B77/a/4,7) - both in clear weather with southerly flow. These two occasions coincided with the highest values at Eastmain (92°F) under similar conditions. The modern 31-year extreme at Fort George is 94°F. At the lower limit, the Whale River records show a minimum of -53°F with clear weather and E wind on March 7, 1816, and Alder writes in the Journal "... coldest since January 29, 1812, the year the ship Prince of Wales and crew wintered in the country" (HBC, B372/a/3). This compares with the modern 40-year value of -57°F. The extreme minimum recorded at Big River was -55°F, which is the same as the modern 44-year record for Fort George.

Further evidence of the calibration is provided by the consistency between the readings around 32°F and weather remarks relating to freeze and thaw. In addition, when ice lies offshore in summer, it acts as a regulator of lower temperature limits if the wind blows off the Bay, which offers a further check on the performance of the instrument. For example, at Whale River on August 3, 1816, with heavy ice still offshore, Alder notes in the Journal "... at 11 am 82°F; in the evening at 5 pm 32°F" (HBC, B372/a/3). The Register shows that the morning was clear with easterly flow, but by noon the wind had changed to westerly with thick fog and a temperature of 46°F; the westerly flow and thick fog persisted, and by 5 pm the temperature had stabilized at 32°F, only dropping by 1°F during the night. This cut-off point, at or close to 32°F in the summer months, shows as sharply in the frequency curves of the historical hourly and daily maximum and minimum values as it does in the modern record (cf. Figure 11). I conclude that in spite of the potential for instrumental error in the Type-Six, the actual error was consistently small in the warm-season range below about 50°F, increasing with higher temperatures.

Modern Instruments, 1915 to 1976

The construction, potential accuracy and lag coefficient of the self-registering mercury maximum and spirit minimum thermometers appears to have been virtually unchanged through the modern period 1915 to 1976. For the baseline data period 1957 to 1976, ordinary thermometers used at Great Whale for fixed-hour readings were mercury - more reliable than the spirit thermometers used in the early part of the record. A major change in instrumentation occurred in 1970, when a remote temperature measuring system was installed at Great Whale for the hourly observations.

Thermometers supplied to Canadian network stations into the 1930s were of British Meteorological Office type made by Negretti and Zambra, London, and calibrated to a tenth of a degree Fahrenheit at the National Physical Laboratory before shipment. Later, calibration was carried out in Canada. The observer read all thermometers to a tenth of a degree and applied the necessary corrections. Great attention was paid to the quality of these instruments. In recent years, a distinction has been made between first-order stations, and those climatological stations which measure only daily maximum and minimum temperatures. For the latter, instruments are inspected to comply with an accuracy of ± 0.5°F (±0.3°C), readings are made to the nearest degree Fahrenheit (0.5°C), and no correction is applied - so there is the possibility of an error of ±1°F (±0.6°C) on some occasions. In general, the instrument accuracy has probably been within or close to the limits recommended by the World Meteorological Organization (1954, 1969): maximum thermometers, above 0°F, ±0.3°F (above -18°C, ±0.2°C); minimum thermometers, above 0°F, ±0.4°F (above -18°C, ±0.3°C); ordinary thermometers, above 32°F, +0.1 to -0.3°F (above 0°C, +0.1 to -0.2°C), below 32°F, +0.3 to -0.5°F (below 0°C, +0.2 to -0.3°C).

There are fewer possibilities for instrument error with the mercury maximum than for the spirit minimum, which still shares with the Type-Six the basic defects of spirit noted above. The main hazard with the maximum is undetected damage to the constriction, which may give readings a degree or two low. Since in practice the best thermometers now tend to be sent to the climatological stations, any omission in applying necessary corrections to readings at first-order stations might incur an error of as much as ±0.6 or 0.7°F (±0.3 or 0.4°C).

The remote temperature measuring system consists of a dry-bulb thermistor in the screen and a temperature indicator (galvanometer) in the station building. Corrections are applied for calibration error and to allow for the length of cable. The accuracy of the system is about ±0.2 to 0.3°F (±0.1 to 0.2°C), but it requires both care in operation and regular checks against the mercury thermometer, otherwise errors could become larger and more erratic than with the ordinary thermometer. A limit of ±1°F (0.6°C) is placed on the permissable difference between the remote system and the mercury instrument.

While systematic errors were most likely greater for the historical instruments, non-systematic errors of up to 1°F (0.6°C) or more apply to both early and recent periods.

Instrument Exposure

In their discussion of the role of instrument calibration in data quality assurance, Champ and Bourke (1978) note that "the major error can be, and in fact usually is not in the indication of the instrument, but in the exposure of the sensor, and/or in the assumptions regarding interaction of the sensor with its environment". If this is so with modern screening, it is even more important when the thermometer is an integral part of the outside environment, as in the early nineteenth century.

Modern Screening and Siting

The standard exposure for modern station temperature records is designed to obtain a temperature representative of the free-air circulating in the locality, and by minimizing the unique nature of each site, to permit direct comparison from one site to another. In order to come close to the "true" air temperature, all direct effects of solar, sky and terrestrial radiation, rain and snow, on the thermometer must be minimized by screening, without interfering too greatly with the flow around the instrument. During the period under discussion, some form of the Stevenson screen has been used in Canada. With the Stevenson, the greatest departures from free-air temperature generally occur on sunny days with light winds, when the screen can produce readings 1 to 2°C above the temperature of the ambient air; on clear quiet nights, the radiational cooling of the structure may give readings as much as 1°C too low. Owing to the lag of the screen, the natural fall in temperature in the late afternoon is slower in the screen, as to a lesser extent is the rise during the morning. Also, after rain, the air inside may be cooled below that of the free air by evaporation from the shelter.

However, true air temperature is itself difficult to define owing to the small-scale temperature fluctuations in space and time, and some form of standardized smoothing is required. A degree of spatial smoothing is obtained by regulations (World Meteorological Organization 1954) to assure an open, unobstructed exposure, with the thermometers installed from 1.25 to 2 m over level terrain of short grass, or in its absence the natural earth. A certain time-smoothing of the small-scale temperature fluctuations is caused by the combined lag of the instruments and screen in measuring true air temperature. Ambient air temperature at these heights can fluctuate by as much as 2°C in 10 minutes and at times in less than a minute. This low-level turbulence tends to be greatest in sunny weather with low to moderate wind speeds; the fluctuations are intensified by increased surface roughness, and in the presence of a light, cold breeze. For a representative air temperature under such conditions a lag of several minutes is required. The lag coefficient[1] of the Atmospheric Environment Service instruments is about 90 seconds in near calm conditions; it decreases with increasing ventilation. However, the lag of the Stevenson screen surpasses that of the instrument, varying from about 13 minutes with near calm conditions to about 2.8 minutes with winds of 7 m/s (Bryant 1968). The response time also depends on the size of the screen; larger screens have a longer lag.

Exposure and the Homogeneity of the Modern Temperature Series

The various modern instrument sites at Great Whale, Fort George and Eastmain have on the whole fulfilled requirements, with the exception of Great Whale 2 (1952 to 1957), where the screen was installed near the edge of the 18-m terrace overlooking the river. The surface properties of the northern sites are, however, very different from the standard short grass cover.

A certain inhomogeneity may have been introduced at Fort George and Great Whale by changes and discrepancies in the screening and ventilation, and by poor maintenance. At Eastmain, no changes appear to have been made during the short record 1960 to 1976.

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[1] The lag coefficient is defined as the time required by the thermometer to respond to 63% of a sudden change in temperature.

Differences in screening at these three settlements must also be considered when comparing data. These discrepancies in temperature are sensitive to weather conditions.

(i) Fort George. The "thermometer shed" shipped in 1915 was probably a Stevenson with iron louvres, installed in standard manner. By 1956, an old large-size Stevenson was in use, with wooden-louvred sides and ceiling. This was most likely set up about 1933; it remained until the station closed in 1969. In 1956, the screen was considered well-exposed, but its condition only fair. The rain gauge and sunshine recorder were mounted on top, and wooden steps resting against three sides added to the mass and blocked ventilation. By 1963, both the condition of the screen and its exposure had deteriorated further.

Compared with the standard Stevenson screen, some differences would be expected in both the maximum and minimum records. From 1915 to ~1933, the presence of metal could, if not well maintained, have induced relatively higher daily maxima and slightly higher minima in the short subarctic night, and possibly lower minima in late autumn. The large screen (~1933 to 1969), given its condition, the obstructions and the presence of bare sand, would have resulted in consistently higher monthly mean daily maxima (up to about +0.4°C, or more, with high sun) and mean daily minima (up to about +0.2°C, or more, especially in autumn) (cf. Köppen 1915; Sparks 1972).

(ii) Eastmain. Here the screen is smaller than the standard. Reference to Bilham (1937) suggests that this results in consistently higher monthly mean daily maxima, although the differences are small over grass (warm season, ~0.2 to 0.3°C); monthly mean daily minima are consistently lower (warm season, ~0.1 to 0.2°C). The presence of organic terrain may emphasize the differences, especially when the surface is very dry. As discrepancies in maximum and minimum are of opposite sign, the effect on the monthly mean daily temperature is small.

(iii) Great Whale. It is believed that the screen sent up in 1925 was similar to the iron-louvred Stevenson at Fort George, and that the exposure was good. The change to a standard wooden-louvred model probably occurred about 1940. In 1955, a standard motor-ventilated Stevenson was installed, and new screens of this type were installed again in 1957 and 1970. With the latter, the sensors for fixed-hour readings are situated in a duct in the lower left of the screen, and air from the screen is sucked in at 7.6 m/s. Besides assuring a constant rate of flow, the duct provides these instruments with additional shielding. While aspiration appears to reduce the lag of the screen near the air intake, it is doubtful whether it produces any significant change in the rate of ventilation in the higher areas of the screen, where the maximum and minimum thermometers are located. Since the selected hourly data base refers to 1958 to 1976, this set is considered homogeneous with respect to exposure. Besides the early period with iron louvres, other factors to be considered include: (1) general deterioration of the screen and exposure from 1961 to 1970; and (2) the continuous running of the ventilation motor after 1970 — the air released above the screen has been heated by 1.0 to 1.7°C in passing over the motor. Of unknown effect is the change in screen ventilation (and the frequency of the observer's presence) arising from opening the door 24 times a day from 1957 to 1970, as against two to five times for the remaining record. Also, the Stevenson is not considered a good radiation shield over snow, which raises the question of the greater reflectivity from sandy surfaces in dry, sunny conditions, following the mass removal of vegetation cover in the mid-1950s. With low wind speeds, there is also stronger heating of the three staggered boards which form the floor of the screen. Generally, these factors tend towards overheating.

While it is difficult to express these inhomogeneities quantitatively, perhaps useful lower limits can be set from Smith's (1951) experiment over grass at Kew. For standard naturally-ventilated Stevenson screens, his results showed a "random" error in daily maximum temperature readings from -0.6 to +1.1°C, with 95.4% of the observations within ±0.3°C. For minimum temperatures, the limits were ±0.6°C, 95.4% within ±0.2°C. In the case of the hourly temperatures, Smith's limits were ±0.6°C. For aspirated fixed-hour readings, there is evidence of greater variability. Departures from standard screening tend to increase observed daily maximum temperatures; the effect on the minimum can be positive or negative, but is generally smaller. Through compensation, the error in the mean daily temperature may be small but is generally positive.

In Table 2, I have attempted to estimate confidence limits for screen temperature as a measure of ambient air temperature at these three weather stations. They take into consideration the results of a comparison between screen and aspirated psychrometer readings at Downsview (McTaggart-Cowan and McKay 1976), field measurements made over the sand at Great Whale with an aspirated Bendix Psychron, and the local discrepancies in screening.

(i) At Great Whale, greatest overheating of the screen (> 0.6°C) occurs consistently with clear or partly cloudy skies (≤ 7/10), low to moderate wind speed and dry surfaces. Wind speed is more important than cloud amount.

(ii) Small but variable differences (up to ±0.4°C) occurred with typical Bay weather — cool, damp, often windy conditions with low, heavy cloud cover; they were least in the

TABLE 2: *GREAT WHALE, FORT GEORGE, EASTMAIN, BASELINE DATA: ESTIMATED CONFIDENCE LIMITS FOR SCREEN TEMPERATURES, INCORPORATING (I) INHOMOGENEITIES DUE TO DEVIATIONS FROM ATMOSPHERIC ENVIRONMENT SERVICE STANDARD SCREENING AND/OR MAINTENANCE, AND (II) DIFFERENCES BETWEEN SCREEN AND AIR TEMPERATURE.*

GREAT WHALE

Hourly Temperature 1957-1976

Hourly readings +1.0 to −0.5°C

Monthly means		10-yr monthly means	
Noon to 3 pm	*≤ +0.5°C*	*Noon to 3 pm*	*≤ +0.3°C*
6 am to 8 am	*±0.2°C*	*6 am to 8 am*	*±0.1°C*
5 pm, 6 pm	*≤ +0.3°C*	*5 pm, 6 pm*	*≤ +0.2°C*

Daily Maximum and Minimum Temperature 1925-1976

Daily readings: maximum +1.3 to −0.6°C; minimum +1.0 to −0.7°C
Monthly means: maximum ≤+0.7°C; minimum +0.4°C
10-yr monthly means: maximum ≤+0.4°C; minimum ±0.2°C

FORT GEORGE

Daily Maximum and Minimum Temperature 1915-1969

Daily readings: maximum +1.7 to −0.5°C; minimum +1.0 to −0.6°C
Monthly means: maximum ≤+0.9°C; minimum +0.6 to −0.3°C
10-yr monthly means: maximum ≤+0.5°C; minimum +0.3 to −0.2°C

EASTMAIN

Daily Maximum and Minimum Temperature 1960-1976

Daily readings: maximum +1.5 to −0.6°C; minimum ±0.8°C
Monthly means: maximum ≤+0.8°C; minimum +0.3 to −0.6°C
10-yr monthly means: maximum ≤+0.5°C; minimum +0.2 to −0.3°C

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absence of fog or precipitation.

(iii) Largest negative differences between screen and ambient air (≥0.6°C) were related to three sets of weather, all typical of this coast during the warm season. In the first, precipitation is the dominant factor. The second and third combine bright sunshine with strong low-level diffusion, multiple reflection and absorption (i.e. the presence of a thin veil of low cloud or fog with the sun plainly visible, conditions which frequently occur with light to moderate NW to N winds; or in sunny, very dry weather, with strong, dessicating SE to S winds, low-level aerosol and blowing sand particles). Although the Psychron may have overestimated air temperature, given the strong diffuse and reflected radiation, these results are of particular interest with regard to the unscreened, outdoor exposure of the historical instruments. Nights of calm, or low wind speeds are usually associated with cloud, minimizing radiation loss from the screen.

Over a period of 20 years or more, differences between monthly screen and air temperatures would probably be positive but very small. Screen errors are believed to show most clearly in months of extreme warmth or extreme cold related to anticyclonic situations, when the screen allows overestimation of air temperature. At Great Whale, these screen errors have been underscored by removal of the vegetation cover and change in station site.

Historical Instrument Exposure

The exact siting and exposure of the thermometers at Whale River, Big River and Eastmain are not on record. Journal remarks for Eastmain indicate that the instrument was outside. General exposure appears to have been similar at the three Posts, since the temperature series are very alike in the pattern of their differences from the modern data (cf. Figure 10).

At this period, it was generally accepted that the thermometer should be located out-of-doors, that the sun should at no time shine directly on the instrument and that reflection from nearby walls should be avoided. The question of distance from buildings was under debate. The Royal Society favoured a north-wall location, and a 5- to 10-cm separation from the wall was considered adequate. It seems that while conduction was taken into consideration, the effects of long-wave radiation were underestimated. It was not until the end of the 1830s that the Society began to be actively involved in the development of forms of shaded stand, and later, screens, to house the thermometers. On sifting the evidence, I believe that thermometers at these three Posts were installed on the north wall of the Master's house at a height of 1.2 to 1.5 m. This assumption is basic to this study.

When the thermometer is directly exposed to the elements, the lag of the instrument becomes critical, as does its unique "viewpoint". Without the obstruction of the screen, even the lower wind speeds are more effective in reducing the response time. Both hourly and daily maximum, minimum observations of ambient air temperature are therefore more sensitive to small-scale temperature variability through convective and mechanical turbulence, and to rapid changes of cloud, weather or surface conditions. Although in the shade, the thermometer remains subject to scattered and reflected short-wave radiation and heat from the environment, closely related to the material composition and detailed geometry of the settled site, as well as the daily routine and life-style of the inhabitants. In this region, this is emphasized by the nature of the surface and sky conditions, the presence of late spring snow, the use of wood as building material, the need for heat indoors during much of the season, single glazing, and poor insulation. On the other hand, there is the degree to which the instrument is exposed to rain and snow. Detailed reconstruction of the settled sites was undertaken based on Journal entries over a number of years; for Eastmain, plans and a painting (Figure 6) were also available.

The North Wall Versus the Stevenson Screen

Gaster (1879) compared temperatures from an open north-wall exposure with those in an early Stevenson screen, mounted in the open over grass. In spite of possible discrepancies between the wall-mounting, the greater heat storage capacity of a brick wall compared with wood, and the differences in surface environment and weather between southern England and the east coast of Hudson Bay, Gaster's results offer some basis for discussion.

(i) Overcast weather. Differences began to appear in April/May. At 9 am, the wall averaged ~0.6 to 0.8°C higher and at 3 pm about 0.6°C above that of the screen. Even at 9 pm, the north wall was still a little warmer. In July/August, the direction of the differences remained the same, but the amplitudes were greater. For October/November, deviations were small but still positive at 9 am and 9 pm, and negligible at 3 pm.

(ii) Sunny weather. In spring and summer, the wall exposure was again warmer at 9 am and 9 pm, but at 3 pm mean temperatures were lower than for the Stevenson. For autumn, the average temperatures were close to the screen values, although differences showed more variability than with overcast. With partly cloudy skies, the variations were intermediate between clear and overcast.

(iii) Daily minimum temperatures, like those at 9 pm, were higher at the wall in all weather. The average daily maximum, unlike the 3 pm, was lower than that in the screen for both sunny and overcast skies.

(iv) The number of days when the thermometer was found wetted by rain, fog or dew was very low.

The question then arises as to whether these patterns of difference are valid for the three Hudson's Bay Posts on the Bay. As explicit assumptions are required in the calibration of the historical temperature data, the different energy balance components at the north wall were carefully considered in the light of the literature. A brief summary is given below.

Energy Exchanges at a North Wall

The daily global (direct + diffuse) short-wave radiation falling on a north wall in clear summer weather is only about 20 to 30% of that for a horizontal surface. The amount of direct sunshine is small, even in midsummer (Figure 8A) — at Great Whale, an hour or two after sunrise and before sunset, May to August; the historical temperature series for morning and evening show no evidence of direct radiation. Besides the morning and evening global maxima on clear summer days, Kondrat'yev (1977) suggests that there is a third, less pronounced peak about noon. In these northern regions, this may be enhanced in sunny weather by the effect of the local qualities of the terrain and cloud on scattered and reflected radiation, and the frequent thinning and opening up of the cloud around midday. In general, the percentage of diffuse to global radiation increases with decreasing solar elevation and decreasing atmospheric transmissivity. With overcast and a snow cover, a north wall can receive up to 80% of the global radiation for a horizontal surface; a fraction of 50% is assumed with a heavy, low overcast and damp, snow-free surface conditions. Figure 8(B,C), gives some indication of the effect of the wall shadow on solar radiation received by the ground below; in summer, the depletion is confined to a distance of about one half the height of the structure.

On the other hand, owing to its exposure, the north wall receives more long-wave radiation than the horizontal. Also, heat loss at the wall, and for the ground just below, is only 50% of that in the open — although at the ground, the fraction increases rapidly with distance from the wall (Figure 8C). This is of considerable importance, not only in the nocturnal radiation balance, but because it increases the effectiveness of all long-wave radiation received from heated surfaces and other heat sources in the immediate environment.

Owing to surface roughness created by buildings, stockades and so on, it is conceivable that in sunny weather, the turbulent exchange of sensible heat between sunlit areas and objects and the shaded north wall provides a further compensating mechanism - particularly given the thermal properties of such surfaces as sand and wood. And the unscreened thermometer picks up the fluxes more readily. The nature of the turbulence when the wind direction is perpendicular to a fence or building is modelled in Figure 9. In general, whether the regional or local wind is from S or N, air flow is directed towards the wall at

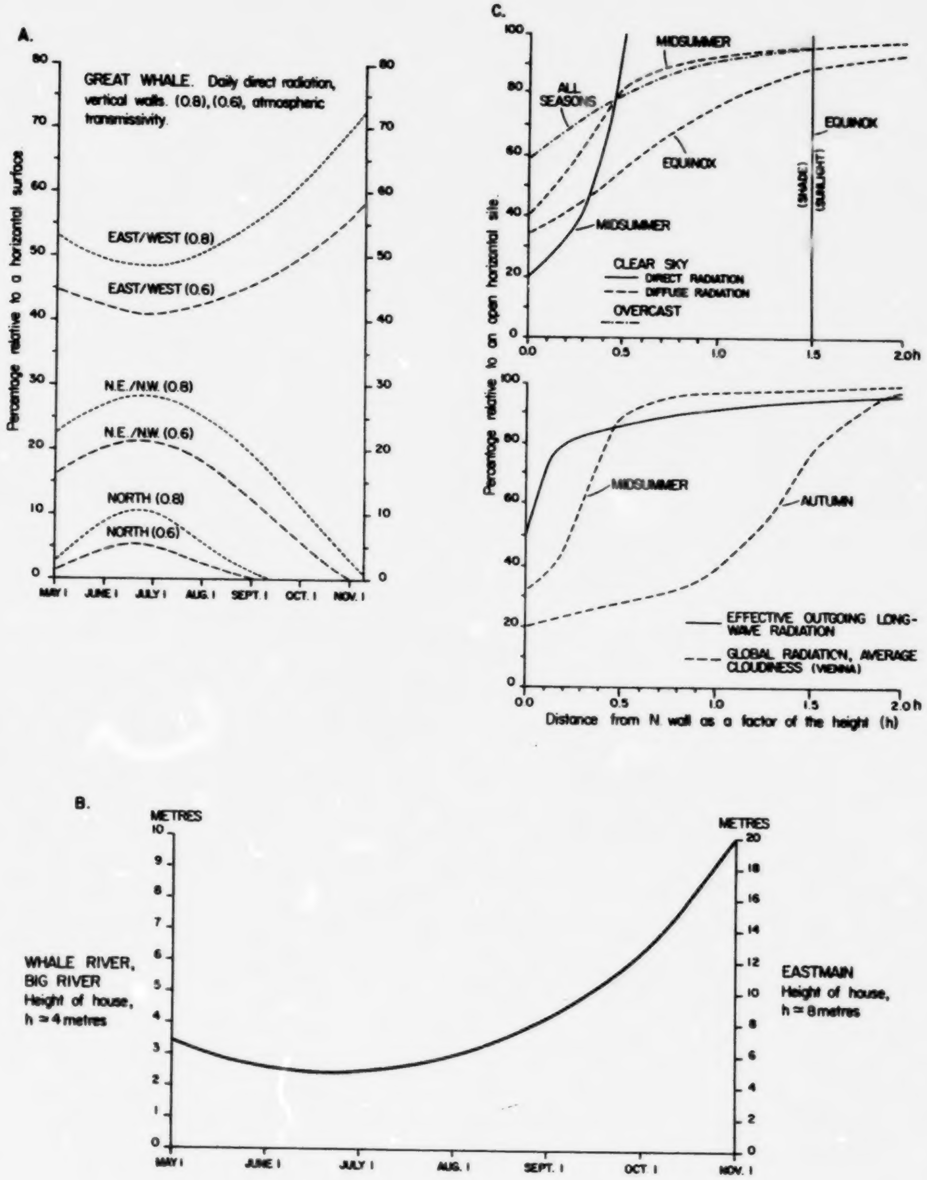


FIGURE 8: *Radiation at and just below a north wall in comparison with an unshaded horizontal surface: A. Daily direct solar radiation received at the wall; B. Length of shadow cast on the ground by the north wall at noon; C. Percentages of daily solar incoming radiation ($48^{o}N$) and effective outgoing long-wave radiation at the ground, as a function of distance from the north wall. (Dirmhirn 1953; Bolz,* In *Geiger 1965, p. 343.).*

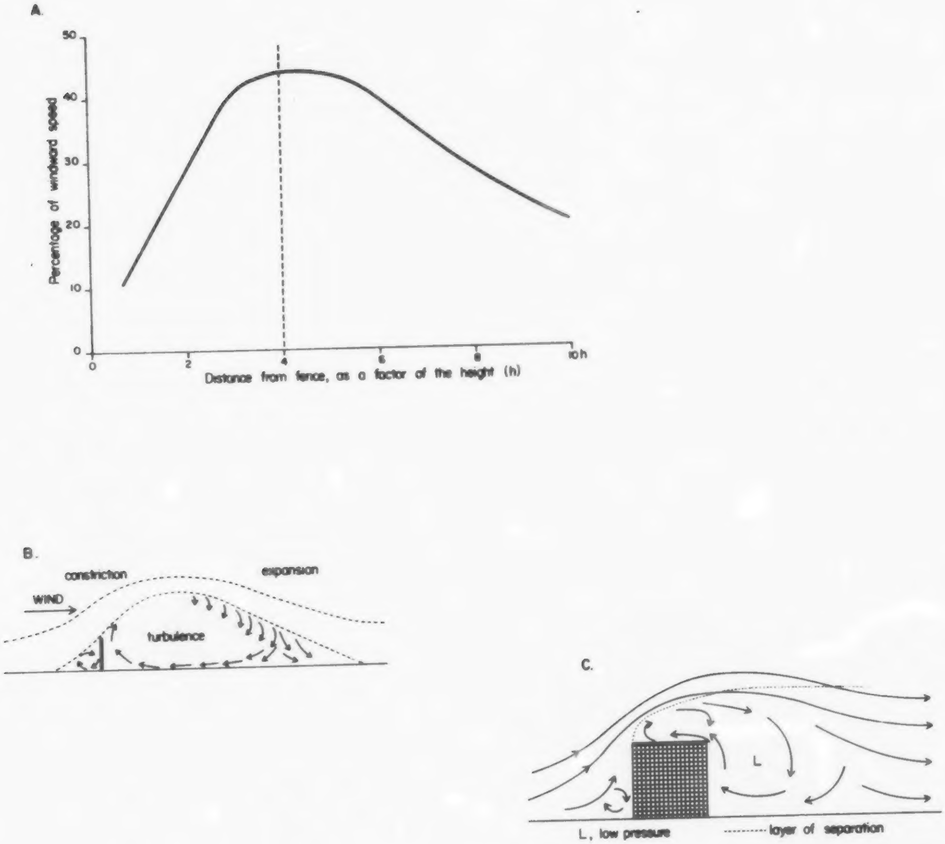


FIGURE 9: *A. Reduction in wind speed in the lee of a solid fence (after Moysey and McPherson,* In *Darby 1971); B. Wind flow over a solid fence (after Belot* et al. *1972); C. Wind flow over a building (from Bourque 1976; Munn 1966, after Halitsky).*

1.5 m. A further heat source is that escaping from the building interiors. Concerning evaporative heat exchanges, the key is the degree of shelter afforded by the north wall. Driving rain or fog is usually associated with SW to W winds, but heavy showers can occur with NW flow. Although the number of days with precipitation is large, the probability of precipitation at an observing hour is much lower. When the sensor is wetted, the temperature reading is lowered by evaporation to that of a wet-bulb thermometer.

Temperature Differences Arising from the Historical and Modern Exposure

To estimate limits of temperature differences which could result from the open north-wall exposure compared with a modern Stevenson screen, differences obtained between a north-wall screen and a Stevenson are compared with those between an open Glaisher stand and the modern screen, again for southern England. The north-wall screen provides the limiting case for shading from environmental short-wave and long-wave exchanges, when these influences on the thermometer are reduced to a minimum. The Glaisher stand (Glaisher 1868) combines an open northerly aspect with almost unimpeded exposure to reflected short wave and terrestrial radiation from the sunlit ground below. Temperature differences for an open north-wall exposure probably lie between these two extremes. The average monthly differences (all weather) are given in Table 3.

To sum up, the subarctic north-wall sites probably differ from that of Gaster's rural Rectory in southern England, firstly in the greater amount of reflected and diffuse sunlight; secondly in the larger contribution of environmental long-wave radiation and sensible heat; and thirdly in the larger loss of indoor heat to the outside, occasioned by the colder weather, the manner of building and the larger number of inhabitants. Bearing in mind these differences, and others implicit in Gaster's results, and with references to Table 3, the following assumptions are made for the three Bay Posts:

(i) Monthly mean daily minimum and mean morning and evening temperatures were either higher or similar to those of the modern series. Monthly differences were probably not greater than +0.5°C - most in summer, least in autumn.

TABLE 3: *AN ASSESSMENT OF THE LIMITS OF ERROR, WHEN THE THERMOMETER IS PLACED ON A NORTH WALL RATHER THAN IN A STEVENSON SCREEN: A COMPARISON OF TEMPERATURE DIFFERENCES BETWEEN (I) A NORTH-WALL SCREEN (NW) AND A STEVENSON (MARRIOTT 1879), AND (II) A GLAISHER STAND (GG;GK), AND A STEVENSON (ROYAL OBSERVATORY GREENWICH 1902 to 1911; STAGG 1927). DATA ARE FOR SOUTHERN ENGLAND, WHERE MONTHLY DIFFERENCES TEND TO BE CONSERVATIVE FROM YEAR TO YEAR.*

MEAN DAILY TEMPERATURE		°C	M	J	J	A	S	O	YEARS
Mean Daily Maximum		NW-STEV[1]	+0.3	+0.3	0.0	−0.1	−0.9	−0.7	1
		GG-STEV	+0.9	+0.9	+1.2	+1.0	+0.6	+0.3	9
Mean Daily Minimum		NW-STEV[1]	+0.6	+0.8	+0.8	+0.4	+0.5	+0.3	1
		GG-STEV	−0.3	−0.3	−0.3	−0.3	−0.3	−0.3	9
Mean Daily Temperature		NW-STEV[1]	+0.4	+0.5	+0.4	+0.1	−0.2	−0.2	1
		GG-STEV	+0.3	+0.3	+0.4	+0.3	+0.2	−0.1	9
MEAN HOURLY TEMPERATURE		**°C**	**M**	**J**	**J**	**A**	**S**	**O**	**YEARS**
Morning	7 am	GK-STEV	+0.5	+0.4	+0.3	+0.3	+0.1	0.0	3
	9 am	NW-STEV	+0.2	+0.2	+0.1	−0.2	−0.7	−0.7	1
		GG-STEV	+0.3	+0.3	+0.3	+0.2	+0.2	+0.1	9
Afternoon	Noon	GG-STEV	+0.3	+0.4	+0.4	+0.3	+0.2	+0.1	9
	1 pm	GK-STEV	+1.3	+1.1	+1.2	+1.1	+0.8	+0.4	3
Evening	6 pm	GK-STEV	+0.3	+0.3	+0.5	+0.2	−0.2	−0.3	3
	9 pm	NW-STEV	+0.3	+0.3	+0.6	+0.2	0.0	−0.1	1
		GG-STEV	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	9

[1] Adjusted to refer to the modern Stevenson, which is slightly cooler than the earlier model.

(ii) The monthly mean daily maximum and noon values probably showed larger positive differences. An analysis of the nine years of daily values for the Glaisher stand at Greenwich showed that the largest overreadings of the daily maximum occurred either with strong solar radiation and afternoon cloud of 5 or 6 tenths, and on days with 9 to 10 tenths cloud cover; both sets of days were dry, with winds SSW to W, lighter than average. Unlike Gaster's case, it is believed that positive differences might have occurred near midday in sunny weather as well as under overcast at the Bay Posts. This effect would likely be more marked for the noon reading than the maximum, where it is dampened by overheating and lag of the screen, and most apparent between May and August. Largest differences might be anticipated at Eastmain, owing to the nature of the Post and instrument. The smaller differences at noon for Greenwich, compared with Kew (Table 3) are believed to be the result of an inconsistency in the exposure of the ordinary thermometer bulb, and the values for Kew are preferred. Unfortunately, there were no midday readings for the north-wall screen.

With an overcast and northerly winds, or damp conditions, or strong winds, little difference would be expected between north wall and Stevenson.

(iii) Although all differences at the Bay Posts appear to be weighted towards the positive, the monthly mean daily temperatures were probably within +0.6 and -0.2°C of the modern record (see Table 3), at this season.

Observing Practices

For the modern period, there have been procedures to standardize the reading and recording of temperature, and the timing and number of fixed-hour and daily observations. In the early nineteenth century, many of the ground rules had still to be formalized.

With the exception of the first year (1814-15) at Whale River, the 1814-1821 weather records for these three Posts were presented in the "standard" format of the Royal Society. At this period, at least two or three "fixed-hour" observations were made per day -- morning, midday and evening. The importance of the timing and punctuality of these readings was not stressed by the Society until the late 1820s. Hence a variety of hours was used from one site to another, and from one year to the next. In the early nineteenth century, the significance of the time of the daily observation of maximum and minimum temperature was not yet recognized by the Society. Potential differences between the historical and modern series at the three Bay Posts, arising from timing and other observing practices, are discussed below.

Timing of the Fixed-hour Temperature Readings

There is evidence of some debate by the Masters on the timing of the meteorological observations, at regional headquarters (Moose Factory) in late summer 1815, and again in 1816. I consider that the patterns of timing selected at these Posts (Figure 2) were generally adhered to.

Reference to the modern record at Great Whale indicated that changes in observing hours between noon and 3 pm would produce small average "errors", generally within +0.2 and -0.1°C from May to October. On the other hand, changes in morning or evening hours can introduce large discrepancies in some months. For example, the change at Eastmain from 8 am to 6 am calls for a reduction in the mean hourly temperatures of ~1.3 to 1.7°C in late spring and summer. The corresponding evening correction from 8 pm to 6 pm is ~+0.9 to 1.3°C. The greatest potential for error with respect to punctuality is around 8 am and 8 pm from May to August. Modern practice (based on Eastern Standard Time) allows a 10-minute leeway. The solar time used at the Posts is 10 to 15 minutes behind the Standard. If the historical readings had been made a few minutes early, this could have introduced a small negative error in the morning, positive in the evening; otherwise readings would probably have been close to the modern tolerance.

Timing of the Daily Maximum and Minimum Readings

The mean daily temperature in Canada is defined as the average of the daily maximum and minimum readings. However, the climatological day (the 24-hour observing period) has differed through the modern record, and between classes of weather station. Inhomogeneities which result are associated with the time at which self-registering maximum and minimum thermometers are reset, in relation to the daily heating cycle. If the start of the day is close to the time of the daily maximum, the temperature carried over into the next day may be higher than the true maximum for the day, and the monthly mean daily maximum is too high. Similarly, if the start of the day is near the time of the daily minimum, the monthly mean daily value is too low. The three definitions of the climatological day of concern here are:

(i) Type A, from 1 am to 1 am, for both maximum and minimum. Introduced at Great Whale, July 1, 1961, this consistently results in monthly mean daily minimum values that are too low. The average error is about 0.7°C May to July, falling to 0.3°C in October; in some spring and summer months it can be as much as 1.1°C.

(ii) Type B, from 8 am to 8 am for the maximum; from 6 pm to 6 pm for the minimum. This was essentially the case at Great Whale from 1925 to 1961, at Fort George from 1933 to closure in 1969, and for the Eastmain record.

(iii) Type C, from 5 pm to 5 pm for both maximum and minimum. This was apparently the case for Whale River and Big River, 1814 to 1821 (cf. Six 1782), and results consistently in monthly mean daily maximum values that are too high. The average error is 0.8 to 0.9°C May to July, falling to 0.3°C in October; in some spring and summer months it can be as much as 1.4°C. While the monthly mean daily minimum values are homogeneous in this respect with most of the modern record, they will read too high in relation to the Great Whale series from July 1961. At Fort George, 1915 to 1932, the observing day was about 9 pm to 9 pm, which would give slightly lower minimum and higher maximum temperatures.

Thus, as they stand, historical monthly mean daily maximum and minimum temperatures are higher than the Great Whale data base 1957-1976, as a result of differences in the start of the climatological day. To simplify the calibration procedure, the historical values have been reduced to comply with a 1 am-to-1 am day. Correction factors were derived from hourly data at Great Whale over 30 months, and are given in Table 4. Where necessary, readjustment to the mean daily minimum to comply with a Type-B day can be made in the final correction (Table 4).

Other errors arising from observing practices apply to both periods, but may have been more significant in the nineteenth century, particularly for the mercury thermometer at Eastmain. These include the effect of heat from the observer's body, breath or touch (a positive error), the angle at which the thermometer is read, and the mental division of the scale. These tend to become systematic for a given observer. A study of Figure 2 suggests few changes of observer from 1814 to 1821.

CALIBRATION OF THE HISTORICAL TEMPERATURE DATA: QUALITY CONTROL

In the final analysis, the conscientiousness and reliability of the observer and recorder are the crux of the matter, and mistakes in reading the instruments and transmitting the values can be difficult to detect. The psychological setting at remote stations, today as in the past, is not always conducive to the kind of self-discipline required. Larger mistakes can often be spotted by visual inspection of the record, and where the logic of the error is clear, a correction can be made; otherwise the data are rejected and estimated values may be substituted. In scanning for suspect data in the modern Canadian record by computer, temperature values are compared with limits of past occurrence. The difficulties are many for climatic change studies: if all data beyond the limits of past experience are rejected, new extreme values may be missed; if wider limits are accepted, the "new extremes" may be simply observing or recording errors (Potter 1969).

TABLE 4: ***SUMMARY OF CORRECTION FACTORS APPLIED TO HISTORICAL MONTHLY TEMPERATURE VALUES: a) CORRECTION TO ACCOUNT FOR DIFFERENCES IN THE START OF THE CLIMATOLOGICAL DAY: b) CORRECTION FOR INSTRUMENT ERROR, DIFFERENCES IN SITE AND INSTRUMENT EXPOSURE, AND RESIDUAL ERROR. (SLIGHT DISCREPANCIES IN "TOTAL" CORRECTION RESULT FROM THE ROUNDING AND CONVERSION TO DEGREES CELSIUS).***

WHALE RIVER, BIG RIVER		M	J	J	A	S	O
Mean Noon Values °C	b)	-3.3	-3.3	-3.3	-2.5E	-1.3	-1.3
Mean Daily Maximum °C	a)	-0.8	-0.9	-1.1	-0.8	-0.7	-0.3
	b)	-1.7	-1.7	-1.7	-1.4E	-0.9	-0.9
Total correction		-2.5	-2.6	-2.7	-2.2	-1.6	-1.2
Mean Daily Minimum °C A. With respect to the Great Whale model (and monthly record from July 1961).							
	a)	-0.7	-0.7	-0.7	-0.4	-0.6	-0.3
	b)	0.0	0.0	0.0	0.0	0.0	0.0
Total correction		-0.7	-0.7	-0.7	-0.4	-0.6	-0.3
B. With respect to the rest of the modern record.							
	a)	0.0	0.0	0.0	0.0	0.0	0.0
	b)	0.0	0.0	0.0	0.0	0.0	0.0
Total correction		0.0	0.0	0.0	0.0	0.0	0.0
Mean Daily Temperature °C A. With respect to the Great Whale model (and monthly record from July 1961).							
	a)	-0.8	-0.8	-0.9	-0.6	-0.6	-0.3
	b)	-0.8	-0.8	-0.8	-0.7E	-0.4	-0.4
Total correction		-1.6	-1.7	-1.7	-1.3	-1.1	-0.7
B. With respect to the rest of the modern record.							
	a)	-0.4	-0.5	-0.6	-0.4	-0.3	-0.2
	b)	-0.8	-0.8	-0.8	-0.7E	-0.4	-0.4
Total correction		-1.3	-1.3	-1.4	-1.1	-0.8	-0.6
EASTMAIN		M	J	J	A	S	O
Mean Noon Values °C	b)	-4.8	-3.5	-3.2	-2.2	-1.8	-0.8
To Adjust 8 am and Sunrise to 6 am Readings, °C	1814	-	-	-	-	-	-0.3
	1815	-1.4	-1.5	-1.7	+0.1	0.0	0.0
	1816	+0.6	+0.9	-	-	-	-
To Adjust 8 pm and Sunset to 6 pm Readings, °C	1814	-	-	-	-	-	+0.3
	1815	+1.3	+1.1	+1.1	+0.4	0.0	-0.4
	1816	+1.3	+1.1	-	-	-	-

N.B. BIG RIVER, EASTMAIN: Where mean daily temperature has been predicted from morning and evening values, the following correction is required to compensate for the low minimum temperature in the Great Whale prediction model. This also applies to WHALE RIVER, if comparison is made with the modern record prior to July 1961:

°C	a)	+0.3	+0.4	+0.4	+0.2	+0.3	+0.2

The Early Nineteenth Century Records

Examining the records (Figure 2), two features are noteworthy: first, and assuming that all the data are bonafide, the rarity of "missing" observations in the series; second, the extended gaps in the records during summer and early autumn. The latter arose through the absence from the Post of the Master and Clerk, who sailed to Moose Factory with the annual trade and reports. The Meteorological Register was usually kept up until the day of sailing, and recommenced immediately on return. The 1814 directive from the Company to the Bay Posts (A6/18) had stressed the importance of having the Register maintained through the growing season, and Post Journals and Annual Reports are often explicit concerning the cause of a break in record.

Thomas Alder, Master at Whale River and Big River, was 45-years-old in 1818 and had lived 23 years on this coast; his considerable knowledge of the region was recognized by the Company. The most reliable set of observations was probably from 1815 to 1819, when Philip Good was Clerk (and weather observer) — described by Alder as assiduous and a correct and able accountant. During Good's term, daily extremes and three fixed-hour temperatures were recorded. Alder himself queries the reliability of Atkinson's Register for 1814-15, describing him as careless and inattentive. James Russell, Master at Eastmain 1814 to 1817 was rather a pompous man with a puritanical streak, who found it difficult to maintain discipline. His experience on the Bay was limited, but he was fortunate in his Clerks. George Gladman Sr., who took over as Master in 1817, had spent most of his life on the Bay. He himself was a careful observer, with a genuine interest in weather and the natural environment. On his own initiative, he had ordered the new thermometer for Eastmain in 1806. His son George, described by Russell as pleasant and agreeable, and well-qualified for the position, was Clerk in 1815-16 and from 1817. The least reliable year of record was probably 1814-15.

Briefly, I believe that with respect to the quality of the early temperature series, the Masters and Clerks at these three Posts were highly motivated and by nature likely to make as reliable a record as the instruments, their siting and exposure and the observing practices of the time permitted. The Company, which expected to gain financially as a result of the observations, could be severe in its displeasure, and the lives of most of these men were deeply rooted in the region so that they had no wish for dismissal.

Canadian Quality Control Procedures

The procedures and limits have been published by Potter (1969). Although this type of work generally requires decisions by technical and professional staff, five checks have been set up by the Atmospheric Environment Service to enable the computer to be used to flag suspect data. Four are applicable to the historical temperature series:

(i) Type A. To check that an observed value is within certain limits. The limits are either estimated or based on actual limits of past occurrences: e.g. daily maximum and minimum temperatures.

(ii) Type B. A check for consistency: that the relationships between temperature and other weather occurrences are acceptable (e.g. temperature and type of precipitation); also that daily maximum temperature is greater than the minimum.

(iii) Type D. A check for change with time (e.g. day-to-day, or hour-to-hour variations against given limits).

(iv) Type E. A check for change with space (e.g. a comparison between stations of daily temperature readings, against imposed limits).

The modern daily and hourly temperature series for Great Whale, Fort George and Eastmain have therefore passed through quality control. The evaluation of all types of hourly weather data for Great Whale, 1960-1969 (Atmospheric Environment Service 1970) shows a rating of fair or lower for most years - although not a good one, it was as good, or better than most remote stations in Canada during these years.

Initially the 1814-1821 series were carefully checked for obvious errors, and relatively few were found. The entries in the Registers were then compared with weather remarks in the Journals. The major discrepancy appeared to be an error in dating by the new observer at Big River in July and August 1819. The data were then scanned according to the general specifications set out by Atmospheric Environment Service for checks A,B,D,E, and also against actual limits based on past observations at Great Whale and Fort George. For daily data at Whale River and Big River:

(i) Type A. the monthly extreme temperatures were within modern limits with three exceptions: the minimum was 0.6°C (1°F) lower in July, 1816 and 2.2°C (4°F) lower in May 1817; the maximum was 5.0°C (9°F) above the modern record in May 1818.

(ii) Type B. The extreme daily range was never beyond the general Atmospheric Environment Service limits, but for five months was just outside the station limits for 1957-76; the only large difference was 6.7°C (12°F) for August 1816, for which there is some justification.

(iii) Type D. The changes in the temperature from day to day were always within limits for the minima. For the daily maxima, differences were from 1 to 4°C (2 to 7°F) beyond 1957-76 limits on five days only.

(iv) Type E. No comparison was possible.

Regarding hourly data at the three Posts, all were within the general Type-A limits, and only seven hours showed inconsistency with the Type-B check; of these, six cases were marginal. As Potter (1969) suggested that the Type-D check for change in time becomes less valuable for intervals greater than an hour, this was not applied to the individual data. For Type E, no comparison was possible.

Clearly, the historical series easily pass the modern Quality Control checks, with just a slight hint of higher maximum or noon values, and that another form of procedure is required.

Extension of Quality Control Procedures for Historical Data

A study was made of monthly differences between the mean fixed-hour readings, and the mean daily maxima and minima, at each Post, in comparison with those for Great Whale 1957-76. This is basically an extension of the Type-D quality control. The differences for Whale River and Big River in June are illustrated in Figure 10. Where two or three hours are combined, the application of Great Whale control data to Fort George and Eastmain should not incur an error greater than about 0.2°C (0.4°F). One of the most striking features of the differences is their consistency both at a given Post and for all sites. Their magnitude decreased in autumn. The results show:

(i) that the differences between the morning and evening values, the morning and daily minimum, and the (morning + evening)/2 and the minimum are within, or close to, modern limits;

(ii) that differences involving the maximum or noon temperatures are exaggerated, suggesting overreading at these times; the exaggeration was greatest at Eastmain.

(iii) that the differences between the daily maximum and noon temperatures were marginally smaller than today.

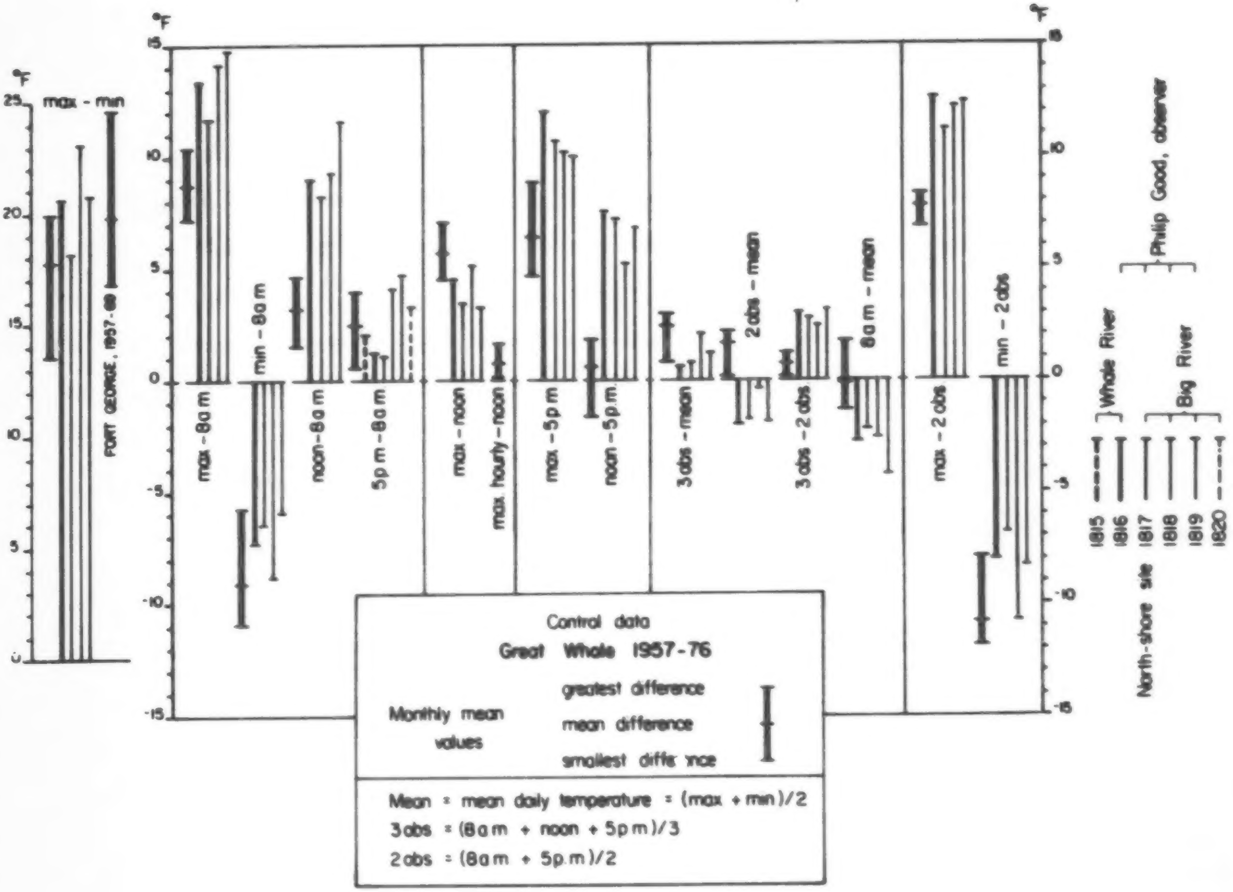


FIGURE 10: *Whale River, Big River (1815-1820). Monthly differences in temperature between mean fixed-hour readings and mean daily maxima and minima in June, compared with the corresponding modern differences for Great Whale.*

The basic correction to account for the 1-am start of the climatological data at Great Whale against 5 pm at Whale River, Big River was then applied to the historical data (Table 4). This brought the historical differences closer to the control data: those between the 8 am and minimum, and (8 am + 5 pm)/2 and minimum were now well within modern limits; a reduction in "error" was shown in differences involving the daily maximum. Compared with the control data, the differences between the daily maximum and noon values are even smaller, suggesting that the error in the noon reading is greater than for the maximum.

As an extension of the consistency check, Type B, the frequency curves of the nineteenth century hourly and daily observations were compared for warm and cold months with similar curves for recent years at Great Whale. Examples for June and July are given in Figure 11: the results are consistent through the season. The histograms are similar in form, the main discrepancy being the relatively higher values at noon in the early period; the limiting effect of the ice and icy waters is as clearly defined in both.

Finally, as a Type-E (space) check, a comparison was made of the time series of daily noon temperatures through the seasons for Whale River/Big River and Eastmain. There was consistency in the rise and fall of daily regional temperature.

Results of the quality control procedures are in keeping with those suggested by the examination of the physical factors of site, instruments and their exposure.

ADJUSTMENT OF THE HISTORICAL DATA

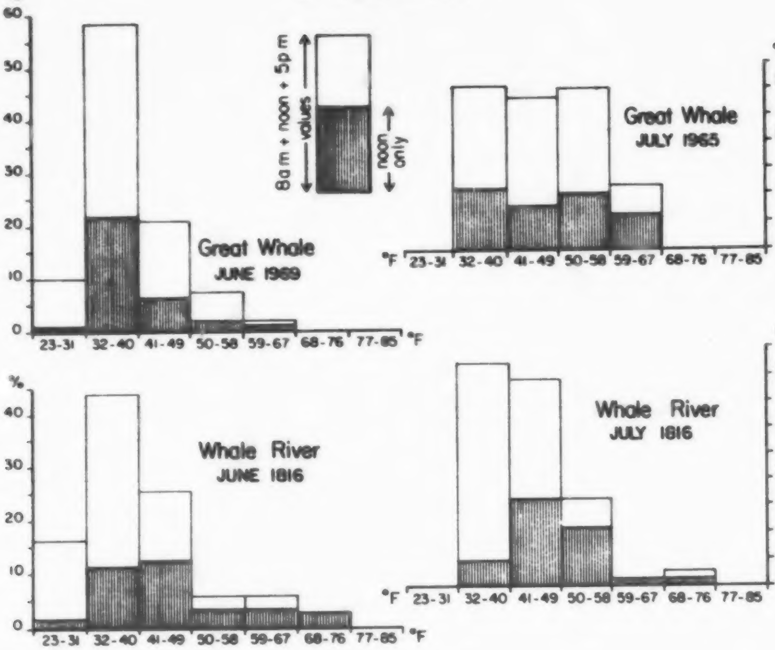
In 1848, Glaisher published a method of reducing the many combinations of fixed-hour observations to comparable mean daily temperatures. His general approach has been followed, with the help of simple linear regression techniques, to obtain correction factors for the historical data. Four basic assumptions are made:

(i) that the self-registering maximum and minimum thermometer was read and reset at about 5 pm at Whale River and Big River;

(ii) that the daily minimum, the 8 am and 5 pm, and the 6 am and 6 pm readings are close to those in a modern screen, or that differences compensate on averaging;

(iii) that the modern temperature relationships at Great Whale were similar in the early part of the nineteenth century;

a) COLD MONTHS



b) WARM MONTHS

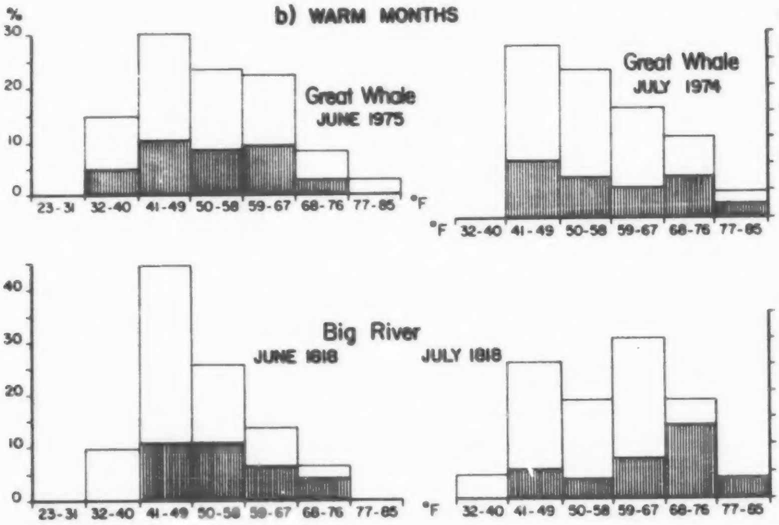


FIGURE 11: *Frequency of hourly temperatures, modern and historical, Great Whale, Whale River, and Big River, 8 am, noon, 5 pm.*

(iv) that the use of the Great Whale baseline data is not too restrictive for Fort George and Eastmain, in spite of the increase in the daily range to the south.

This presupposes that the correction is required to the daily maximum and to the noon values. The method of adjustment is based on the linear relationship which exists over a month between mean daily temperature and the means for given fixed hours, by which the former can be predicted from mean hourly readings. Corrections for mean daily maximum and mean noon temperatures have been obtained from a comparison of modern and historical prediction errors. I have not attempted to correct the individual daily values, but the earlier discussion of probable instrument error and differences arising from instrument exposure, together with the comparison of early and modern histograms, suggest some limits as guide-lines in their use.

Regression Model, Great Whale

Figure 12 shows the regression of the average 8 am, noon and 5 pm, and 8 am and 5 pm temperatures on mean daily temperature, for the 10-yr period 1967-1976 at Great Whale. Both the 3- and 2-hour combinations are similarly useful in predicting the mean daily temperature within 95% confidence limits of ±0.9°C (±1.6°F) - the very warm May 1968 and the cold July 1972 were just beyond the envelope. The points show an internal seasonal grouping — a tendency towards overprediction in spring and underprediction in autumn, apparently associated with different weighting of these hourly observations with respect to night cooling, and dependent on synoptic situation. This seasonal bias was confirmed by dividing the decade, and using the coefficients for each 5-yr set to predict the mean daily temperatures for the other, and studying the prediction error. The whole-season curves thus have a useful diagnostic value. With this in mind, the correction procedure for the noon and maximum temperature is based on these 1967-1976 curves.

To check whether separate coefficients for spring, summer and autumn months might reduce the standard error for prediction purposes, the base period was extended to 1957-1976. For May-June and July-August, there was little change in the confidence limits, but in the autumn they were narrowed to ±0.5°C (less than ±1.0°F).

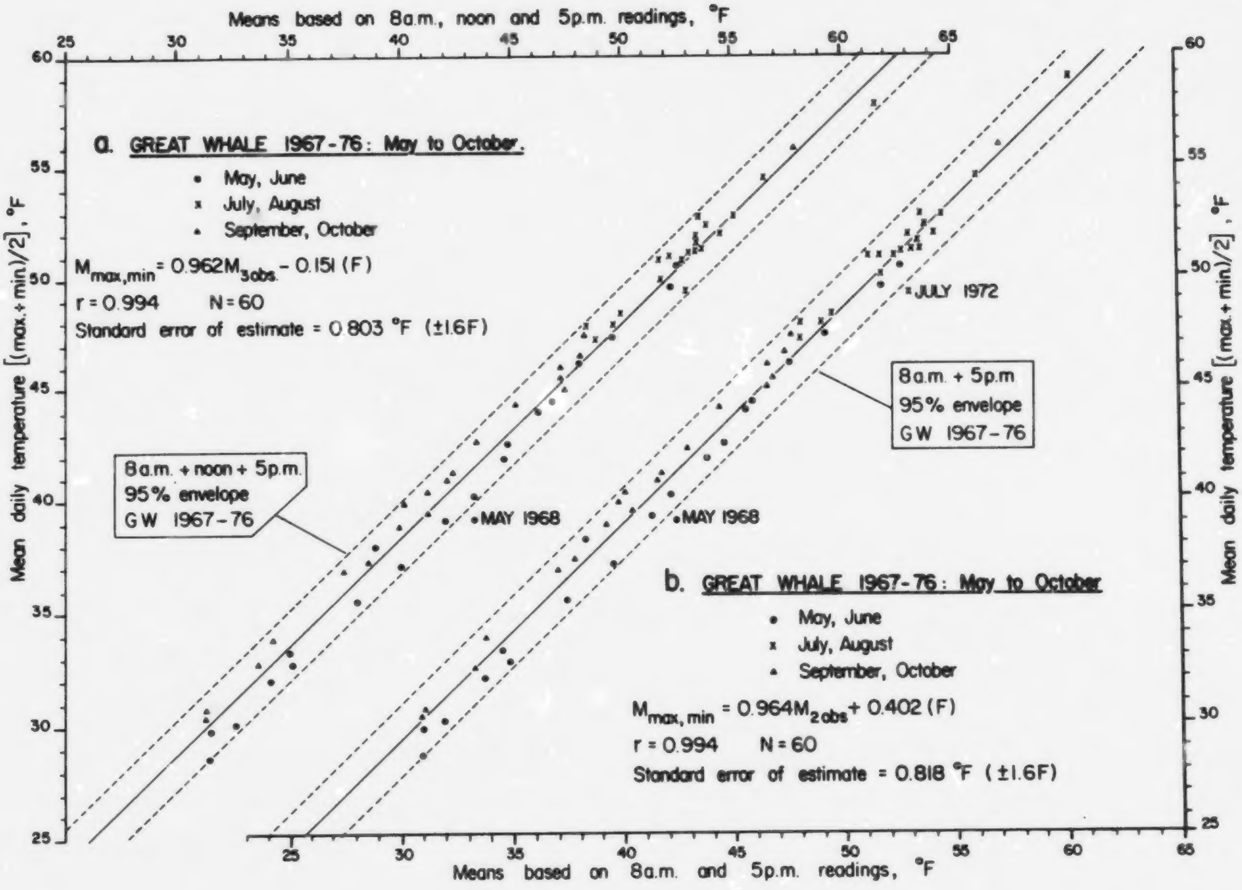


FIGURE 12: *The regression model, Great Whale 1967-76, May to October: a) Regression of mean daily temperature, (max. + min.)/2, on means based on the 8 am, noon and 5 pm hourly readings; b) Regression of mean daily temperature, (max. + min.)/2, on means based on the 8 am and 5 pm hourly readings.*

Relationship Between the Historical Mean Daily and Hourly Observations

Using the 1967-1976 curves, monthly mean daily temperature was predicted for Whale River, and Big River from the 8 am, noon and 5 pm temperature records. Predicted values were then compared with monthly averages of the original maximum and minimum readings (Figure 13). This revealed: firstly, that although the predictions based on the three observations were within the 95% envelope, the distribution of errors was skewed towards underprediction, particularly noticeable in spring; secondly, that this underprediction was even more pronounced when only the 8 am and 5 pm observations were used as predictor.

The correction was then made to the historical observed mean daily temperature to adjust for the difference in the climatological day (Table 4), and this indeed served to reduce the prediction error (Figure 13). For the three observations, the sign and size of the errors now appear to resemble those for the model, but with the two observations, although the reduction is in the right direction the differences remain too large. I believe that in the case of the three observations, the overreading of the noon value is masking the overreading of the daily maximum; with the 8 am, 5 pm predictor, the persistent underprediction reflects directly the positive error in the observed mean daily temperature. From this point on, the correction for the climatological day is incorporated in the historical observed daily maximum and minimum values.

A Correction for the Nineteenth Century Mean Noon Temperature

With the continued assumption that the historical monthly averages, (8 am + 5 pm)/2, are homogeneous with the modern data, the predicted monthly mean daily temperatures for Great Whale 1967 to 1976 based on the three observations were compared with the respective predicted values using only the 8 am and 5 pm readings. Differences arising from the two predictors are shown in Figure 14A, which indicates a near-normal distribution, without seasonal bias. The comparable differences for Whale River and Big River, Figure 14B, show that the three-hour predictor consistently gave higher values (positive differences), and although the cases are few, differences appear to be larger from May to July, with a drop in September and October. Such a bias could well be due to the dampening of the effects of outside instrument exposure and instrument error on the noon temperature in autumn. A

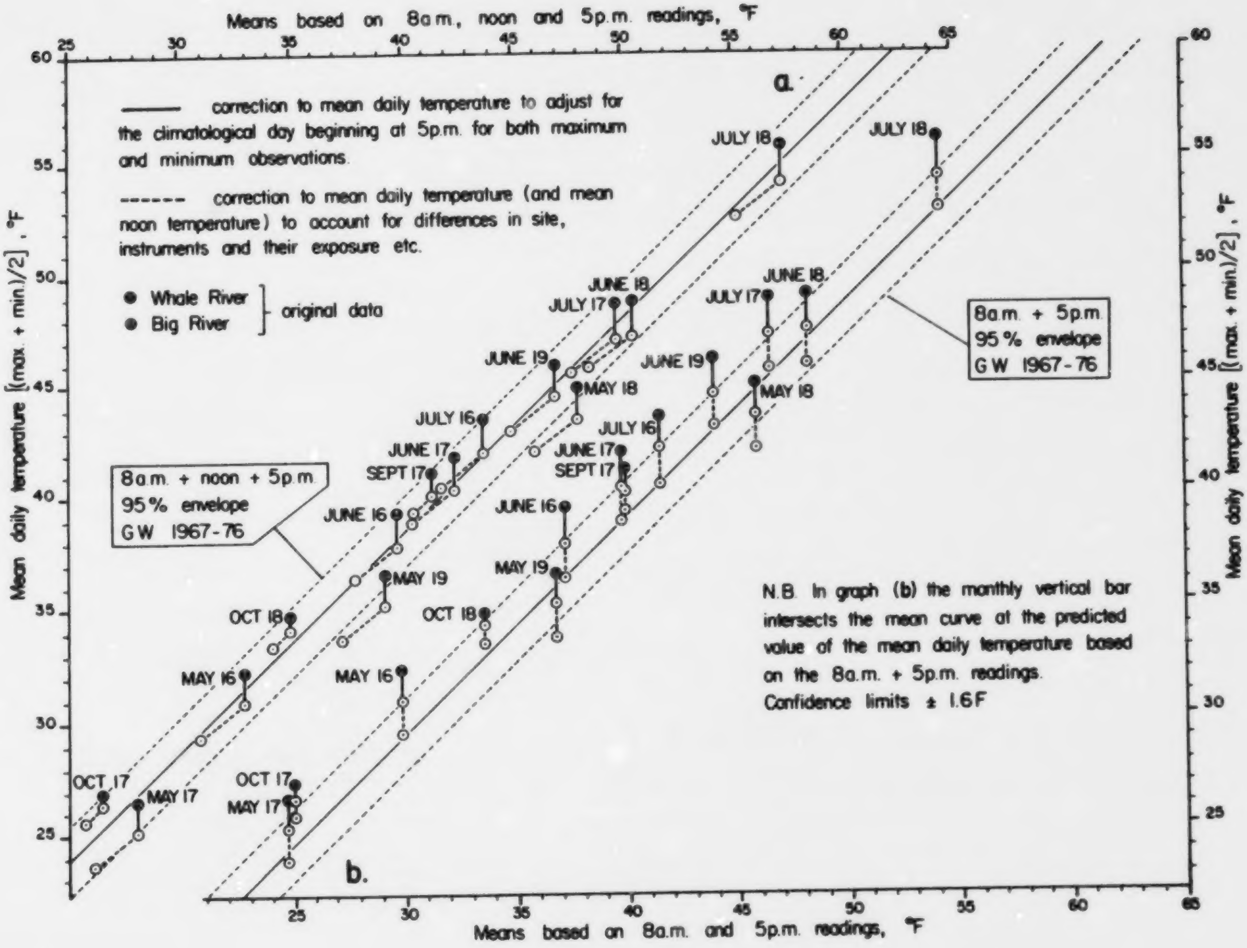


FIGURE 13: *Whale River 1816, Big River 1817-1819: Summary of corrections applied to mean daily temperature.*

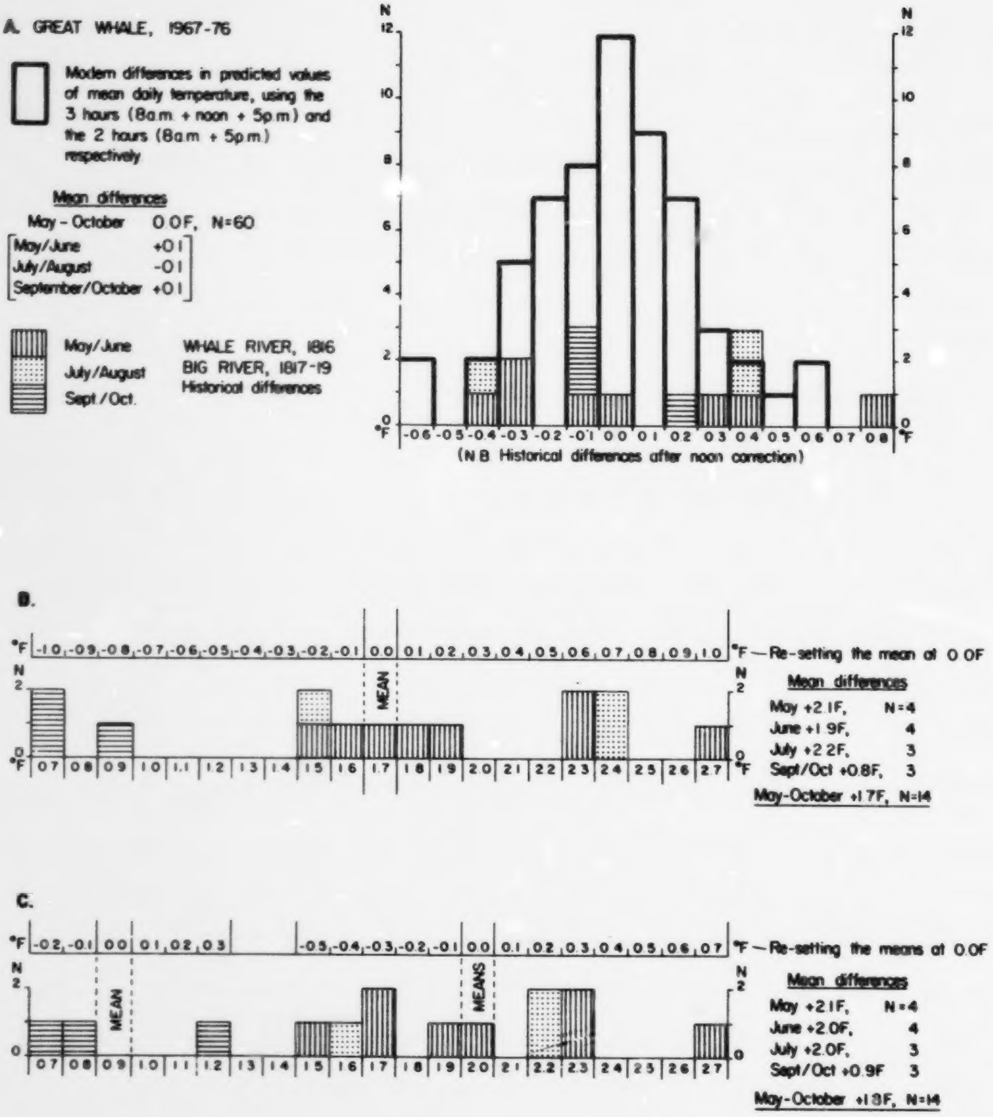


FIGURE 14: *Whale River 1816, Big River 1817-1819. A correction factor for the mean noon temperature: A. Great Whale, 1967-1976, modern differences in predicted values of mean daily temperature, using the three hours, (8 am + noon + 5 pm)/3 and the two hours, (8 am + 5 pm)/2, respectively; B. Whale River 1816, Big River 1817-1819, differences in predicted values, as in A above, based on the 1967-76 regression coefficients; C. as in B above, based on the 1957-76 bimonthly regression coefficients.*

check, using the 1957-1976 bimonthly regression coefficients (Figure 14C) confirmed the distribution of differences.

To obtain a correction factor for the 8 am + noon + 5 pm averages, the mean historical differences, 1.7°F, can be reset to that of the model, 0.0 (Figure 14B). However as the seasonal bias appears real, in spite of the small number of cases, the separate means are used for May to July, and September, October, giving an adjustment of -1.1°C (-2.0°F) and -0.4°C (-0.8°F) respectively; August is interpolated at -0.8°C (-1.5°F). If the 8 am and 5 pm readings are indeed correct or compensating, the corresponding noon corrections are -3.3°C (-6.0°F), -1.3°C (-2.4°F), and an estimated -2.5°C (-4.5°F) in August. For Big River, any difference arising from the greater daily range is negligible for these hours.

A similar procedure was followed for Eastmain, using the 6 am, noon, and 6 pm readings. This combination of hours produces a smaller standard error in the Great Whale model, but a small correction of about +0.3°C (+0.5°F) was necessary to account for the greater daily range at Eastmain. When this adjustment was made, only in spring were the corrections to the noon temperature greater than at Whale River and Big River (Table 4). The seasonal pattern was similar.

A Correction for the Nineteenth Century Mean Daily Maximum Temperature

Retaining the assumption that the historical 8 am + 5 pm mean temperature requires no significant adjustment over a month, the frequency curve was plotted for Great Whale, 1967 to 1976, of the differences between the mean daily temperatures predicted by these morning and evening hours and the observed mean daily temperature (Figure 15A). The comparable curve for Whale River and Big River is shown in Figure 15B. As noted previously, the historical observed values are consistently higher than the predicted. The seasonal bias was confirmed by using the bimonthly regression coefficients. Again by resetting the historical mean errors at those for the model, correction factors are obtained for the mean daily temperature of -0.8°C, (-1.5°F) May to July, -0.4°C (-0.8°F) September, October and an estimated -0.7°C (-1.3°F) in August. Allowing that the mean daily minimum temperature is homogeneous with the modern record, the corrections to the mean daily maximum values are -1.7°C (-3.0°C), -0.8°C (-1.5°F) and -1.4°C (-2.5°F), respectively. This correction accounts for the historical differences in instrument, site and instrument exposure. It is smaller than for the noon readings, which has physical support. No allowance has been made

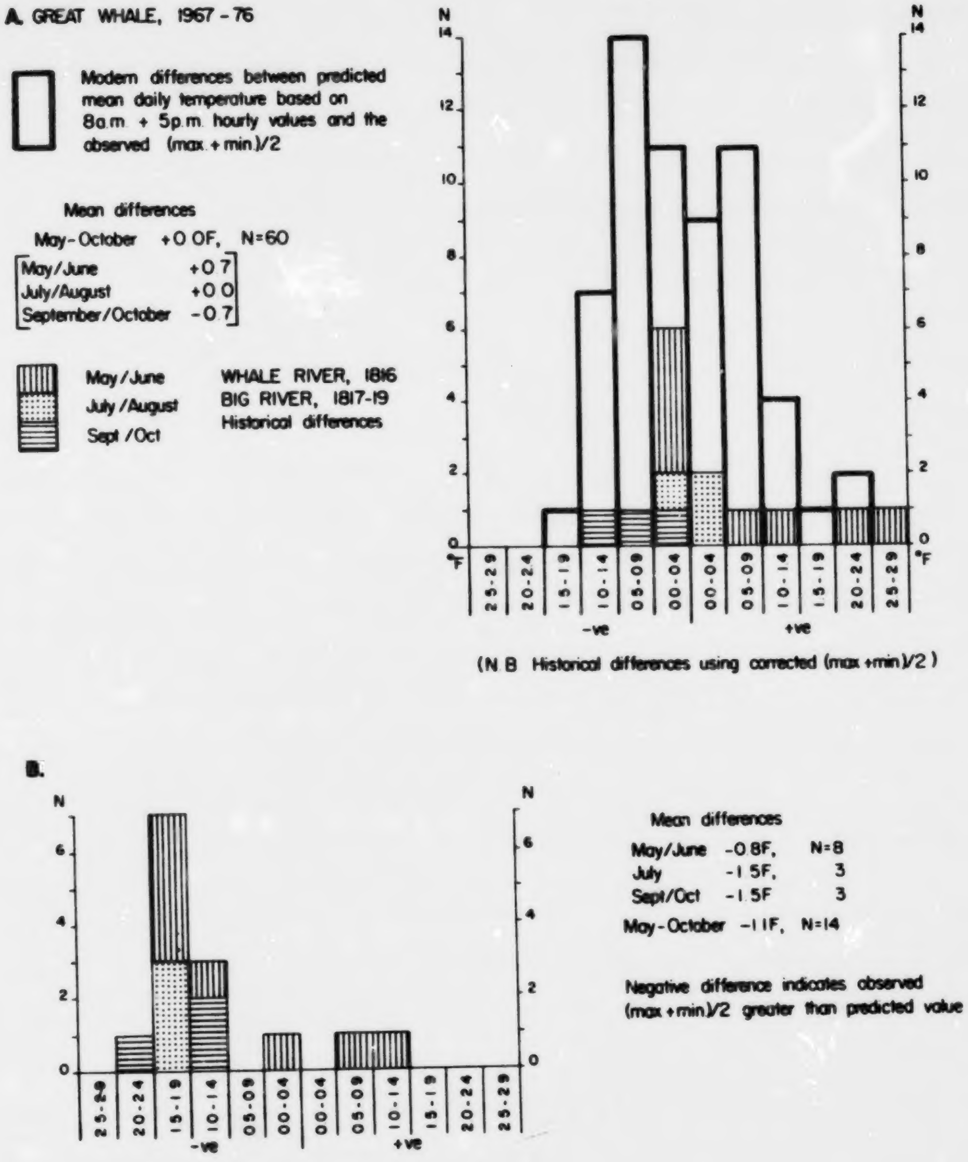


FIGURE 15: *Whale River 1816, Big River 1817-1819. A correction factor for the mean daily maximum temperature: A. Great Whale, 1967-1976, modern differences between predicted mean daily temperature based on the two hours, (8 am + 5 pm)/2, and the observed (maximum + minimum)/2; B. Whale River 1816, Big River 1817-1819, differences as in A above, using the 1967-76 regression coefficients -- all historical mean daily temperatures were previously corrected for the difference in the climatological day.*

for the greater daily range at Big River, but the error is believed to be no greater than 0.2°C (0.3°F). The total adjustment of the historical data is summarized in Figure 13 (with reference to a 1am-to-1am climatological day), and in Table 4.

Mean Daily Temperature, an Alternative Approach

At Whale River and Big River, the mean daily temperature can be predicted directly using the 8 am and 5 pm readings and bimonthly regression coefficients for 1957-1976. Wherever possible, the corrected observed values have been preferred, especially in spring. However, in months where hourly data are are more complete, or the daily data are missing, the predicted values have been accepted. In the case of Eastmain, mean daily temperatures are predicted values, based on the 6 am and 6 pm readings and the coefficients for Great Whale, 1967-76. With these hours the 95% confidence limits are ±0.6°C (±1.1°F). The error due to the greater daily range at Eastmain is believed to be no greater than 0.2°C (0.3°F). For Big River and Eastmain, a small compensation is required to allow for the low minimum temperature in the Great Whale prediction model. This also applies to Whale River, if comparison is made with the modern record prior to July, 1961 (Table 4).

THE REVISED TEMPERATURE SERIES, 1814 TO 1821

The revised mean daily and hourly temperatures are listed in Table 5. There is a marked similarity in the direction and order of the monthly anomalies for all Posts. Compared with those of the modern station series, the mean daily temperatures were on the low side. The 1816 and 1817 seasons were colder than those on modern record. That they were remarkably severe, even for the period, is abundantly clear from the remarks in the Post Journals. Alder, with this 20 years of experience along this coast had never known such extreme conditions. Intense hardships were suffered by both white and native populations as local food supplies failed, and Bay ice played havoc with local communication late into the summer. The situation was made worse when the supply ships from England were trapped by the early formation of ice in Hudson Strait in 1815 and 1816[1], and forced to winter in James

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[1] Ed. note: The difficulties Hudson's Bay Company ships had with ice in Hudson Strait are clearly demonstrated in a paper by Catchpole and Ball (1981, Figures 8-11).

TABLE 5: *CORRECTED MEAN DAILY TEMPERATURE (1814 TO 1821) WHALE RIVER, BIG RIVER, EASTMAIN. GREAT WHALE RECORD (1925 TO 1976); FORT GEORGE (1915 TO 1969). AT EASTMAIN, THE RECORD WAS TOO SHORT TO GIVE A USEFUL ANOMALY. (WHERE VALUES ARE IN PARENTHESIS, MORE THAN FIVE DAYS ARE MISSING.)*

	WHALE RIVER/BIG RIVER							EASTMAIN						
	M	J	J	A	S	O	YEAR	M	J	J	A	S	O	
	-	-	-	-	-	-	1814	-	-	-	-	-	1.2	
	-0.7	1.9	10.6	-	-	(0.2)	1815	-1.2	6.4	(14.8)	(14.6)	6.2	2.1	
Mean Daily	-1.5	2.4	4.7	(5.6)	/	(0.5)	1816	0.3	6.7	-	-	-	-	Mean Daily
Temperature	-4.3	4.2	7.9	6.9	4.6	-3.4	1817	-4.1	3.9	10.9	-	-	(-4.4)	Temperature
°C	5.9	8.1	11.8	-	-	0.9	1818	6.0	9.9	13.5	12.4	9.7	3.9	°C
(Corrected)	1.3	6.5	14.2	12.4	7.1	0.3	1819	3.2	8.0	14.8	12.4	8.4	0.2	(Corrected)
	0.5	10.4	-	-	-	-	1820	2.5	10.3	13.8	12.4	7.1	2.3	
	-	-	-	-	-	-	1821	1.1	8.3	-	-	-	-	
	-	-	-	-	-	-	1814	-	-	-	-	-	-3.5	
	-1.6	-4.4	0.0	-	-	(-2.1)	1815	-5.3	-4.2	(+1.6)	(+2.4)	-3.4	-2.6	
Difference	-2.4	-3.9	-5.9	(-4.7)	/	(-2.4)	1816	-3.8	-3.9	-	-	-	-	Difference
from	-6.8	-4.6	-4.5	-4.3	-3.5	-6.3	1817	-8.2	-6.7	-2.3	-	-	(-9.1)	from
1941-70	+3.4	-0.7	-0.6	-	-	-2.0	1818	+1.9	-0.7	+0.3	+0.2	+0.1	-0.8	1960-72
Normal	-1.2	-2.3	+1.8	+1.2	-1.0	-2.6	1819	-0.9	-2.6	+1.6	+0.2	-1.2	-4.5	Average
	-2.0	+1.6	-	-	-	-	1820	-1.6	-0.3	+0.6	+0.2	-2.5	-2.4	
	-	-	-	-	-	-	1821	-3.0	-2.3	-	-	-	-	
Difference	-	-1.1	-	-	-	-	1815	*	*	-	-	-	-	* Below the
from Lowest	-	-0.6	-2.1	(-1.6)	/	-	1816	*	*	-	-	-	-	Short
on Record	-2.2	-0.7	-1.2	-1.3	-0.6	-1.9	1817	*	*	*	-	-	(*)	1960-72 Record

Bay — an event which was to occur only once again through the century. Furthermore, snow fell in August. There are no reports of August snowfall in the modern record. On the other hand, early spring and summer, 1818, were noted as being unusually favourable by Gladman. The mean daily temperature for May 1818 at both Big River and Eastmain approached the highest on modern record.

Confidence Limits

Statistically, the error in the mean daily temperature at Whale River and Big River is probably within ±1.0°C from May to August, and ±0.5°C in autumn; at Eastmain, within about ±0.6°C. The difference in mean daily range, in applying the Great Whale model to Big River and Eastmain is believed to be less than 0.2°C. However, the results are only as valid as the basic assumptions on which the statistical procedures depend, and it is useful to consider the extent to which historical mean daily temperatures would differ, if alternative assumptions were made:

(i) Assuming no correction is required to the historical readings: upper limits are then provided by the original observations, which are about 1.7°C to 0.7°C (May to October) above the corrected mean daily temperature. All the evidence suggests that this is the least probable solution. Certainly an adjustment would be required for the different climatological day.

(ii) Assuming that the daily minimum, and morning and evening averages are lower than modern screen values: an increase of 0.6°C (1.0°F) to the mean minimum would increase the corrected mean daily temperature by 0.3°C, while a similar increase to the two-hour mean would result in a predicted mean daily temperature 0.5°C higher. As a general assumption, it is not compatible with a north-wall instrument exposure. The historical setting favours the north wall.

(iii) Assuming that the historical daily minimum temperature and the morning/evening averages are similar to modern screen values: ADOPTED HERE, as being most in keeping with the historical, physical and statistical evidence.

(iv) Assuming that the historical daily minimum temperature and the morning/evening averages are too high: this is possible in the case of a north-wall exposure. A decrease of 0.6°C (1.0°F) to the mean minimum would decrease the corrected mean daily temperature by

0.3°C, while a similar decrease to the two-hour mean would produce a predicted mean daily temperature 0.5°C lower. However, this would exaggerate even further the differences between morning/evening and noon readings, and those between maximum and minimum, and require a larger correction to both the daily maximum and noon values.

Thus it appears that realistic changes in the basic assumptions would probably not alter the corrected values of the mean daily temperature by more than about ±0.5°C.

The World Meteorological Organization has recommended ±0.5°C as acceptable limits to modern errors in maximum and minimum readings, and 0.1°C for fixed-hour observations (Sparks 1972). But field conditions are seldom ideal, or consistent through the record, and as Middleton has stressed, the nature of air temperature fluctuations at 1.5 m precludes an accuracy greater than ±0.5°C. The screen itself can overheat by up to 1.0°C during the day, and cool down to 0.5°C below air temperature at night. For Great Whale, Fort George and Eastmain, given the changes and modifications to modern observing sites and practices, the use of screens larger or smaller than the standard Stevenson (at times poorly maintained, or obstructed), the changes in instrumentation, and the differences in observing practices between synoptic and climatological stations, the real accuracy of the modern record is most likely beyond World Meteorological Organization recommendations.

CONCLUSION

There is evidence that temperature observations for Whale River, Big River and Eastmain from 1814 to 1821 were taken with care, and are reliable and consistent within the limitations of the instrumentation, sites, instrument exposure and observing practices of the period. I believe that, in their corrected form, they are accurate to within acceptable limits of error compared with the modern series at Great Whale, Fort George and Eastmain. As such, they indicate that the period was generally cooler than recent times, and that the summers of 1816 and 1817 were colder than any on modern record. As Phase II of this study for the Atmospheric Environment Service, this set of data, together with the other weather information for these three Posts, is now being analysed to provide a detailed climatology of this period, and a comparison with recent climate on the east coast of Hudson/James Bay.

From experience gained in this study, I believe that many of the early Canadian temperature records will amply repay careful calibration. Even if a series is relatively short - as in the present case - it can provide a much needed bench-mark in a time-series based on proxy data, or a case study for comparison with studies elsewhere, particularly with respect to a sensitive region or a sensitive period. The great challenge is to reduce the time required in the calibration, while retaining quality control. An increased understanding of the problem allows a more systematic approach to be taken, and provides a sounder physical basis from which to search for statistical solutions amenable to computer techniques.

ACKNOWLEDGEMENTS

I should like to express my appreciation to the Atmospheric Environment Service for making this work possible, and to the many members of the Service for their encouragement, diverse help and time freely given. Some conclusions concerning instruments and screening were made possible through discussions with Dave McKay and Hugh McCleod of the Instrument Branch of AES. Equally, I have appreciated the permission granted me by the Hudson's Bay Company to use their private archives and the help afforded by the Archivists Mrs. Joan Craig, Mrs. Shirlee Anne Smith and their staff.

Working as a private individual, I have been grateful to the National Museum of Natural Sciences for contact with others working in the field, through association with the NMNS Climatic Change Project, and for the opportunity to publish in *Syllogeus*. The late Gordon Manley was a source of inspiration. I appreciated his unfailing courtesy, interest and help.

Valerie Moore of the Atmospheric Environment Service kindly typed the manuscript, and Edward Hearn of the University of Ottawa, through a contract with the NMNS Climatic Change Project, drafted the diagrams.

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PRELIMINARY ANALYSIS OF EARLY INSTRUMENTAL TEMPERATURE RECORDS FROM YORK FACTORY AND CHURCHILL FACTORY

T.F. Ball[1]

INTRODUCTION

One of the interesting anomalies about early meteorological measurements with instruments is that some of them were made in areas that even today are considered remote. Measurements made by employees of the Hudson's Bay Company in northern Canada in the eighteenth and nineteenth centuries clearly demonstrate this point. The earliest known of these records was maintained at Fort Pitt, Labrador in 1768, and is stored in the archives of the Royal Society in England. Subsequent records are maintained in those archives and in the Hudson's Bay Company archives in Winnipeg. These records are invaluable sources for building a detailed and comprehensive picture of Canadian climate through historic time.

In this paper, I will examine the nature of these records and the inherent problems involved with early measurements, as well as presenting analysis and comparison in the form of daily, monthly and annual means. The nature of the journals and observation methods are examined first. This is followed by statistical and computer analysis of the raw data.

HUDSON'S BAY COMPANY METEOROLOGICAL JOURNALS, OBSERVATION METHODS AND THERMOMETERS

As far as I know, none of the instruments used by employees of the Hudson's Bay Company can be located today. This is not to say that they do not exist, but rather that none has been preserved or retained by the Company. Possibly some remain in the custody of descendants of such ardent early Canadian meteorologists as Peter Fidler, Andrew Graham, and Thomas Hutchins.

Despite the lack of the original instruments, we have some record of the instruments being used. We also know that the impetus for the observations and for use of most of the instruments came from the Royal Society. Doctor James Jurin originated the world-wide, long-term weather observation network that was to occupy the Royal Society for many years.

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> "The system of observations organized by the Royal Society in London from 1724 to 1735 was of great scientific value. The secretary of the Society at that time was J. Jurin, a physicist and doctor who had been a student of Newton. In 1723 Jurin invited scientists of various countries to carry out meteorological observations, and he gave detailed instructions as to the form of the data records." (Khrgian 1970, p. 71.)

Jurin's influence continued for a considerable time, particularly with regard to the format of the recorded observations. Hutchins notes at the beginning of his 1771-1772 record, that in observing the wind he followed the method proposed by Jurin (1722, p. 84) in the Philosophical Transactions. He also followed the order in which the data were to be presented column by column.

Despite the diligence with which the observers followed Jurin's bookkeeping instructions, they were not as fortunate with the instruments. Early instruments provided to the Society were made by Francis Hawksbee, the younger. Jurin had suggested that all instruments should be from his shops in order to allow uniformity and, ultimately, comparison of the results. Most research done on the accuracy and reliability of early instruments shows that Hawksbee's thermometers were not even approximately accurate (Middleton 1969, p. 58). Despite Jurin's advice, later members of the Society used instruments other than those produced by Hawksbee and some of these ended up in the hands of Company employees.

Thomas Hutchins writes in the preface to his 1771-1772 journal that:

> "The instruments used in taking these observations are a barometer and thermometer of Nairne's construction, and we have great reason to think them both very good as Mr. Wales the astronomer (who remarked the last transit of Venus at Churchill) was commissioned to send them. The thermometer is that termed the standard with Fahrenheit's scale; the freezing point is at the thirty-second degree above the Cypher." (Hudson's Bay Company Archives, B239/a/67, p.1)

In 1773 the Royal Society provided several instruments to the Hudson's Bay Company including four thermometers. Unfortunately, these instruments appear to have been in use for some time by various officers of the Company, however the Society only established a research committee on calibration in 1777, thus any records prior to that date must have been kept with instruments uncalibrated according to Society standards. Henry Cavendish submitted a paper on the problems of calibration in 1776 and, as a result, he was appointed chairman of a committee on the calibration and use of thermometers. Unfortunately the major concern was with the upper fixed point, and whether this should be determined by placing the thermometer in boiling water or immediately above in the steam. This is unfortunate, because the upper end of the scale was of little significance in the subarctic climate of Hudson Bay.

Usually the most important thing to determine with early temperature readings is whether the thermometer was protected from exposure to direct rays of the sun.[1] Generally, observers of the Hudson's Bay Company were well aware of the need to shade the thermometer. It is interesting, and important to note, that although there was obviously no knowledge of electromagnetic radiation and the solar spectrum, there was an empirical awareness of the differences between snow that was melting due to above-freezing ambient air temperatures and snow that was melting in direct sunlight. This is best illustrated in various comments made about thawing snow, which show the acuity of the observers as well as giving an idea of the different conditions that can occur. The comments are as follows: thaw, thaw at noon; thaw all day; thaw in lee; thaw in sun; and thaw out of wind.

The earliest records are those of Wales and Dymond, two members of the Royal Society who visited Churchill in 1768-69 in order to observe the transit of Venus. This astronomical event was of great significance for the astronomers but, as with so many things, led to the provision of secondary information of almost equal value. In this case the astronomers were forced to spend a full year (September 1768 to September 1769), because of limited sailing connections, in order to observe an event that lasted approximately seven minutes. As good scientists, they used the time to observe and record as many natural phenomena as possible, including an accurate record of daily climatic information. They note that the thermometers were in shaded locations (Dymond and Wales 1771).

The instruments Wales and Dymond used were sent to York Factory where they were put to good use by the surgeon Thomas Hutchins. Hutchins states clearly in the preface to his meteorological journal that the thermometer was placed on a north-facing wall away from direct sunlight (Hudson's Bay Company Archives, B239/2/67, p. 1). Assuming that the wall was built of unpainted logs, we can probably also say that there was little reflected sunlight.

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[1] Ed. note: For details on such matters see the preceding paper in this volume by C. Wilson.

The last commentary available on recording temperatures is in Doctor John Rae's journal, kept during his year-long stay at York Factory while investigating the loss of the Franklin Expedition. Like Wales and Dymond, he put time to good scientific use by keeping an accurate meteorological journal. A quotation from this journal for 1845-1846 shows that precision of measurement had progressed.

> "The Thermometers were suspended within a couple of inches of each other, under a tunnel like covering of stout canvas, facing north and protected as much as possible from the sun's rays at the same time quite detached from any building. Height of Thermometers from the ground, four feet six inches." (Hudson's Bay Company Archives, B239/2/164, p. 1.)

Between 1769 and 1846 several meteorological journals were kept at both York Factory and Churchill Factory. Apparently one thermometer was in an exposed location because, in 1791, W. Jefferson recorded a temperature of 108°F (42°C). If Jefferson's thermometer was in an exposed location, at least we have reassurance of an awareness of such problems in the memoranda for a Meteorological Journal maintained by Thomas Topping from 1811 to 1813.

> "The Thermometer should be kept where the direct and reflected rays of the sun cannot affect it ..." (Hudson's Bay Company Archives, B42/a/139a, p. 1).

Many problems with early temperature readings can be offset by various mathematical adjustments, but one problem cannot be overcome - that occurs because mercury freezes. This was something that the Royal Society Committee on calibration was not concerned with, although the Committee members must have been aware of the problem based on reports of Wales and Dymond. Mercury freezes at -37.9°F (-38.8°C) but, it becomes increasingly less malleable as that temperature is approached. Therefore, any readings approaching this temperature, and certainly any lower readings, are of little value.

The observers did not consider this a problem, although they were obviously fascinated by the phenomenon. Frequently experiments were carried out but little is resolved, except possibly to allow modern researchers to determine that the ambient air temperature was at least -37.9°F (-38.8°C). For example on January 23, 1821, the journal notes: "Extremely cold quicksilver frozen like a piece of lead" (Hudson's Bay Company Archives, B239/a/133). The same author wrote in 1816, "Weather more intensely cold than ever I knew it before in Hudson's Bay during a period of 25 years having tried the freezing of Mercury ..." (Hudson's Bay Company Archives, B239/a/128). Perhaps we can assume that the author is well aware of the freezing point of mercury, because the word "tried" implies experimentation. In an entry on January 28, 1822, he records:

> "Some quick silver that had been put out some time ago for trying the cold was observed to be frozen while the thermometer was only 36 below zero which proves the weather to have been six degrees colder than per the thermometer." (Hudson's Bay Company Archives, B239/a/134.)

Apparently the observer considered the temperature at which mercury became solid to be -42°F. Because mercury actually freezes at -37.9°F (-38.8°C), it would appear that the thermometer was close to being correct. Fortunately, we are later informed that the observers continued to record the readings without correction. On January 19, 1836 there is a discussion in the daily journal entry concerning the freezing point of quicksilver and the thermometer's accuracy, which ends with an expression of doubt as to the correctness of the records kept for the past five years using a "Gilbert, London" thermometer (Hudson's Bay Company Archives, B239/a/149). In 1838, the observer has either noted an increase in the error or has forgotten his original estimate, for he writes "-35 degree by the incorrect one presently in use here, which when rectified may be registered at -44 degree full" (Hudson's Bay Company Archives, B239/a/151).

The final difficulty with freezing mercury lies in the use of the word "solid" to determine a temperature of -37.9°F (-38.8°C). W. Jefferson provides examples. In January 1790, he noted that "½ oz Quicksilver exposed last night to the Weather was frozen as to bear to be pressed flat with my finger " (Hudson's Bay Company Archives, B42/a/114). Exactly a year later he writes, "Th. -36° three oz of Quicksilver exposed to the weather last night in a marble mortar this morning was so much frozen as to bear to be pressed with my finger and cut with a knife" (Hudson's Bay Company Archives, B42/a/116).

Some questions raised by these comments can only be answered by attempting to recreate the original conditions through experimentation. It was impossible to be rigorous about the methodology employed, because the original experiments were imprecisely carried out and reported. Artificial temperatures were created in a laboratory environment in which a half ounce and three ounces of mercury were tested in an attempt to recreate conditions reported by Jefferson. In addition, the following questions were tested with the results indicated:

(a) What is the range of malleability compared to the range of temperature?

No measurable difference was observed in the reaction of a half ounce and three ounces of mercury. Both began to exhibit a degree of rigidity at approximately -34°F and became solid at approximately -39°C (-38.2°F). The mercury could be pressed flat with a finger, in the manner described by Jefferson, at a temperature of approximately -37°C.

(b) Would the heat of the observer's finger, presumably applied to mercury that had been taken indoors, create its own malleability?

Body heat and pressure would ultimately combine to melt solidly frozen mercury, however it was physically impossible to maintain contact with frozen mercury without freezing a finger! Therefore, it must be assumed that the temperature was somewhere between -36°C and -39°C when Jefferson pressed it with his finger.

(c) Did the use of a marble mortar have any effect?

Similar experiments as outlined above were carried out using a marble mortar. There were no differences in the results obtained.

These experiments indicate that under the preceding conditions mercury is malleable over a relatively narrow range of temperatures. Also, they suggest that the thermometers used by Jefferson were reasonably accurate. One important question remains unanswered; when the observer records that mercury was solid, *had he tested it or was it merely a visual observation ?* This can never be answered definitely, but it seems reasonable that if mercury were placed outside for the purpose of determining its malleability a test with finger pressure is most natural.

Nonetheless, the temperature measurements and the observations are still of great value because they are all that are available for the period and for those locations. Unique problems do not normally affect the accuracy of the readings, but they are frustrating to the observer and historical climatologist. Two examples of this type of problem are found in the York Factory journals. In one instance the thermometer was broken by Indian children, and although the surgeon attempted to repair it with gum arabic he had no success. The second example involves removal of mercury from a thermometer for use as medicine.

The time at which the observation was made is of much greater concern when instrumental records are being studied. Fortunately, thee is a high correlation between the precision of the instrumental readings and the observer's awareness that a regular schedule is required. As a result, only one record lacks the time of observation. This is Peter Fidler's record. All other records note observation times, although those times are not consistent from record to record. Generally there are three readings each day - a noon reading being the one most persistently observed.

PRELIMINARY ANALYSIS OF THE HUDSON'S BAY COMPANY TEMPERATURE RECORDS FROM YORK FACTORY AND CHURCHILL FACTORY

Treatment of the Data

The value of these instrumental records cannot be overstressed, as they will probably provide absolute measures for comparison with modern records and also serve as calibration points for proxy data. Here, I give a preliminary analysis of the early instrumental temperature records from York Factory and Churchill Factory. More detailed studies have not yet been undertaken. Daily, monthly, and annual mean temperatures have been calculated and are tentatively compared to the modern record for Churchill.

For the purposes of this study, I assumed that the data were totally acceptable and that any errors would be within normal limits. Evidently the thermometers were kept in appropriately shaded external locations, used the standard Fahrenheit scale, and the observers followed scientific procedures outlined by the Royal Society. Wilson (personal communication), who has studied Hudson's Bay Company records maintained at Great Whale River[1] during the nineteenth century concludes, that these early records are apparently comparable in quality to modern ones maintained in the same locations.

The longest modern meteorological record at Churchill runs from 1953 to 1979. So I decided that, although this was an unusual length of time to serve as a base for comparison, it was preferable to have as long and continuous a record as possible. A comparison of the range of temperature observations on each day of the year for historic and modern records is shown in Figure 1. The highest and lowest reading for each day of the year during the period of record illustrates the variation in the range of temperatures. Note that the two records are similar in their pattern, adding validity to the historical data. More importantly, they both show a wider range in summer and winter, with a definite narrowing in spring and fall. This is in keeping with Catchpole's (1969, p. 256) observations on Canadian Arctic and Subarctic temperature regimes:

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[1] See the paper by C. Wilson in this volume.

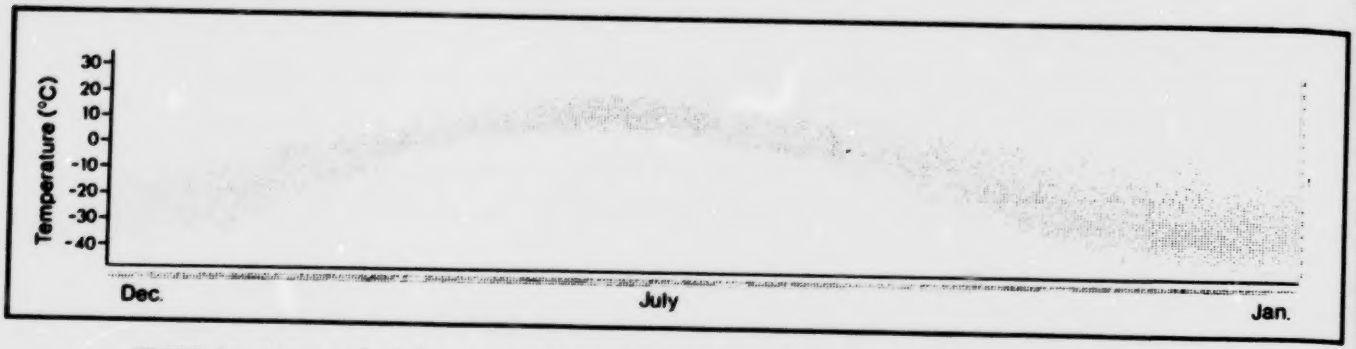

FIGURE 1A: *Range of daily temperature observations for the historic record at Churchill Factory.*

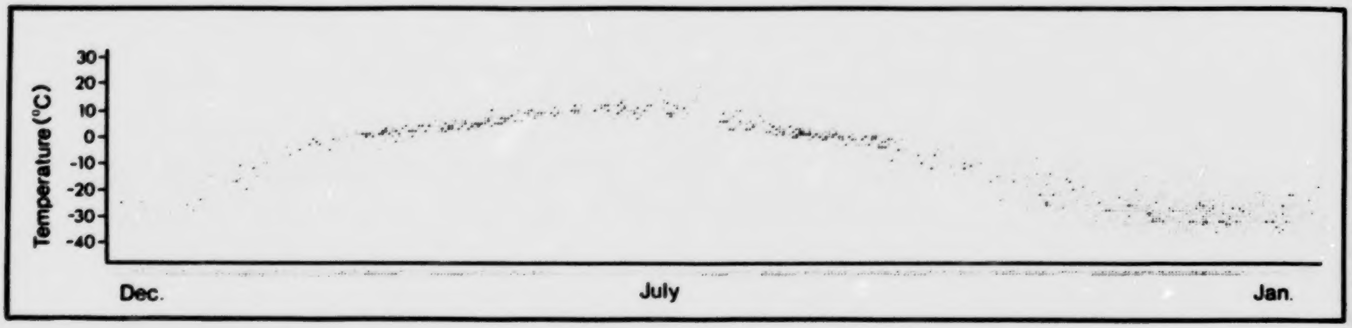

FIGURE 1B: *Range of daily temperature observations for the modern record at Churchill.*

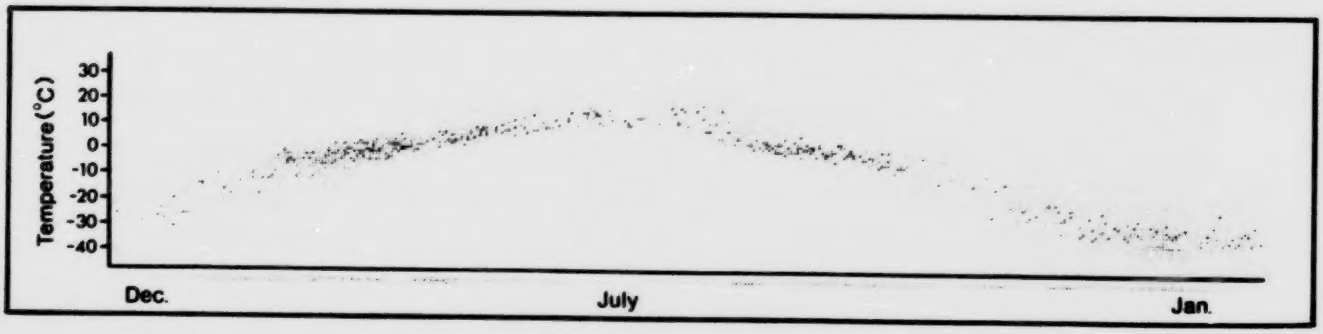

FIGURE 1C: *Range of daily temperature observations for the historic record at York Factory.*

> "The major minimum of mean TR[1] occurs in autumn or early winter, and the minor minimum occurs in spring. Summer emerges, by inference, as a season of strongly cyclical diurnal temperature variations. Irregular variations appear to predominate in winter."

The autumn and spring minima are attributed to the depressing effects of freeze and thaw, which release and absorb latent heat of fusion. Later in the same paper Catchpole (1969, p. 266) states that "... the net effect of the occurrence of the freeze-thaw process over snow or ice-covered surfaces is the reduction of the daily temperature range." Longley (1949), in a study of daily regimes at Québec City, puts an approximate value of 1.1°C reduction in daytime maxima and 0.6°C increase in minima due to freeze-thaw. It would be interesting to see if presence or absence of snow cover could be detected from temperature data if that event were not recorded.

The historic record was examined in order to detect patterns when temperatures were recorded. It was found that up to five readings per day occurred. The number of readings and the times at which they were taken sometimes varied from one day to the next. In order to ensure that the average daily temperature calculated from the historic data would be the best approximation, the following procedure was followed.

From the modern record

$$[1] \qquad t = \frac{t_1 + t_2 \; . \; . \; . \; . + t_{24}}{24}$$

was computed for all days.

Notation: t = average daily temperature

t^1 = estimated average daily temperature

t_1 = temperature at 0100 hours

t_2 = temperature at 0200 hours

t_{24} = temperature at 2400 hours

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[1] Daily range of temperature.

Once the daily averages had been calculated using the 24-hourly readings, it was possible to determine what weighting factor would be necessary, if fewer readings were available. Consider, for example, a day on which three readings were taken, at times a, b, and c.

(1) A regression was run on the modern record for the estimate:

[2] $$t = \alpha ta + \beta tb + \gamma tc + k$$

This gave the weights α, β, γ and the adjustment k.

(2) The estimate

[3] $$t^1 = \alpha ta + \beta tb + \gamma tc + k$$

was applied to all historic records for which readings were taken at the times a, b, and c.

This procedure was applied to all different combinations of the one to five readings which occurred in the historic record. An exception; readings of unknown time, one per day, were recorded as t_{24} since there were no recorded midnight readings in the historic record. In these cases, the following estimate was used:

[4] $$t^1 = t_{24}$$

I assumed that correction factors calculated from the modern Churchill record would be applicable to the historic record of both Churchill and York Factory. If Catchpole's (1969) observations of the differences between snow-covered and snow-free surfaces, and the transition time between those conditions is correct, then the preceding assumption seems valid. Daily temperature-time series are a result of the combined influences of seasonality, warm and cold air masses, a day-to-day persistence effect, and diurnal temperature ranges. Because of similarities in latitude, low coastal plain location, and extent of snow cover, these factors tend to be the same at both sites.

Highlights of the Record from Churchill Factory

Figures 2 and 3 show the plot of monthly mean temperatures for York Factory and Churchill for each of those months when there were sufficient daily readings to make the monthly mean an accurate estimate of the true mean. At Churchill, summer maximum temperatures (usually occurring in July) are consistent with the modern record. It must be kept in mind that these are monthly means, therefore a distinctly cold month, or even a month with a brief cold period, would not show as being distinctly different from an average value. An example of such a problem can be seen in the record for the year 1813, when the

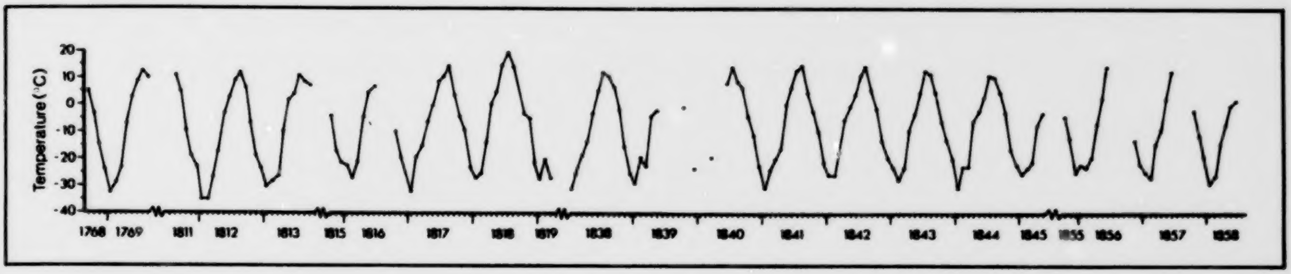

FIGURE 2: *Plot of the monthly mean temperatures for Churchill Factory.*

monthly temperature was recorded as 11.7°C. A journal entry indicates that it was the warmest July for three years, yet this figure is 1.3°C cooler than the modern monthly mean for the period from 1956 to 1972 at the same location.

Apparently winter temperatures for 1768, 1811, and 1812 are well below winter average temperatures of the modern record. Although this is an insufficient sample from which to draw definitive conclusions, it seems to indicate the colder temperatures expected at the end of the Little Ice Age. This is reinforced by the fact that the remainder of the record shows most winters at, or even slightly warmer than, the average temperature for January in the modern record. The only exception to this is the January mean temperature in 1817, when the average was -30°C (modern Churchill average for January is -27.4°C). This might be the result of lowered temperatures occurring after the Tambora eruption in 1815, which apparently resulted in the subsequent year of 1816 being referred to as "the year without a summer".

Other important features in the Churchill record include the following (modern means 1953-1979, for Churchill are given in brackets):

(a) Written comments in the Churchill journals for 1812 note that there was a late spring, May was cold and July had bad weather. These are supported by the temperature data which show monthly averages of April -17.8°C (-11.9°C), May -3.2°C (-2.0°C), June 3.0°C (5.8°C) and July 9.7°C (12.6°C). An indication of cool summers during this period is provided by the comment that July 1813, with a mean temperature of 11.7°C (12.6°C), was the warmest for three years. This period will be referred to again in the analysis of the York Factory record.

(b) Comments are lacking about the temperature at Churchill in 1818, but the York journal notes: "November very mild, mildest for 30 years or more." The reading was -4.7°C (-12.4°C).

(c) 1841, which is noted in the journal as having the latest spring since 1822, has an April mean of -15.9°C (-11.9°C).

(d) June 1842 is mentioned as being cold, and is recorded as 4.2°C (5.8°C).

(e) Generally, summer mean temperatures are consistent for the period of record (Figure 2), while winter temperatures vary considerably.

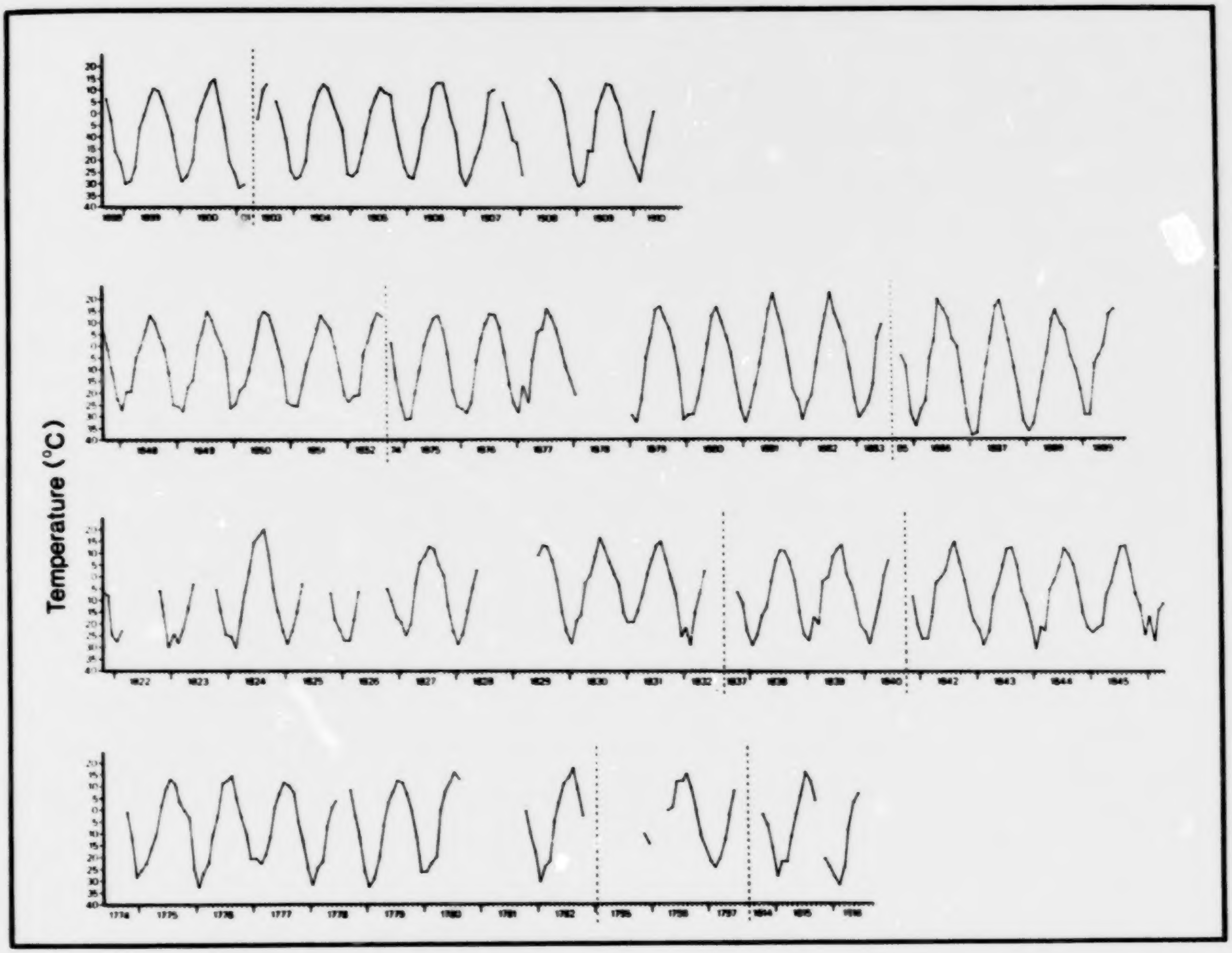

FIGURE 3: *Plot of the monthly mean temperatures for York Factory.*

Highlights of the Record from York Factory

The York Factory record (Figure 3) is much more extensive than that maintained at Churchill Factory, because it was the headquarters of Hudson's Bay Company operations on the Bay. Because the latitudes and sites of the two Factories are similar, I decided that it would be reasonable to combine the two graphs (Figure 4). Where data are available at both sites for the same period (e.g. between 1840 and 1845), the similarity between the curves is striking. It seems to indicate the validity of the data and the decision to combine the two records.

The most notable feature of the York Factory graph is the greater amplitude of the curves for the decade 1879-1889. This period of colder temperatures is coincident with similar colder temperatures recorded at Winnipeg, in southern Manitoba, for the same decade. Records were maintained in Winnipeg commencing in 1874. By 1898, the amplitude has decreased and for the period 1898-1909 the curves resemble those for the period 1775-1780, and 1837-1852.

Other important features of the York Factory record are as follows (modern monthly means for Churchill are shown in brackets):

(a) The period from 1775 to 1779 has below-average summer temperatures. Other records show that each of these summers had above average rainfall, typified by a journal comment for July 1777 noting the wet July and poor summer. In the same year, the Churchill journals remark on the mild winter and late heavy snowfall, conditions that are confirmed by the monthly means for York Factory which were: November (1776) -10.6°C (-12.4°C), December (1776) -21.2°C (-22.8°C), January (1777) -21°C (-27.4°C), February -22.7°C (-27°C), March -19.4°C (-20°C), April -12.2°C (-11.9°C) and May 0°C (-2°C). January and February are considerably above the average, a condition apparently related to the shift in wind patterns - most notably a dramatic decrease in the percentage of north and west winds.

(b) The winter of 1797 was warmer than the average, having an above-average number of days with snowfall, with snow being recorded on 16 days in May.

(c) From 1774 onward there are two periods without temperature records, 1783-1795 and 1798-1821 (except for short gaps in 1814 and 1816). Ironically, these gaps may be due to extremely bad weather, which resulted in harsh conditions for man and animal alike so that survival was more important than record-keeping. Yet, possibly some records are held privately in England - particularly those maintained during the tenure of Joseph

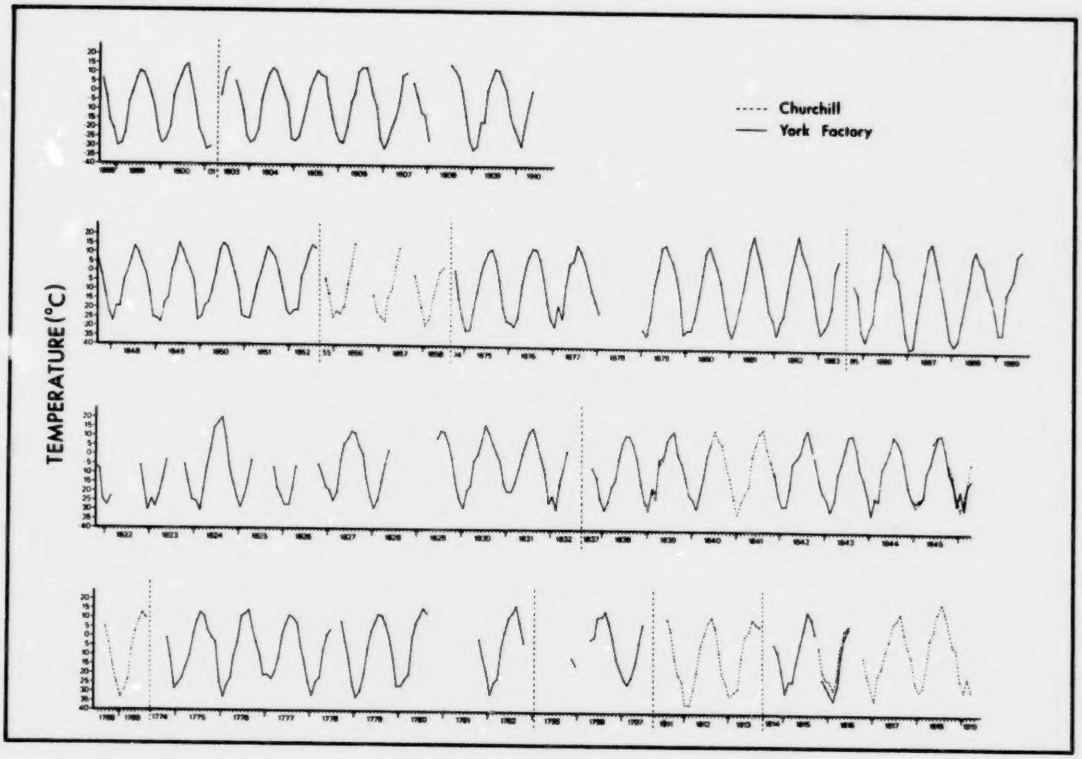

FIGURE 4: *Combined plot of the monthly mean temperature for Churchill and York Factory.*

Colen, who suffered such difficult climatic conditions that there was a dramatic decline in fur take, while scurvy and other illness increased due to lack of game.

(d) A written comment for 1825 stating that there was rain and it was mild in February is supported by the record indicating mildness and an average temperature of -23°C (-27°C).

(e) 1828 is noted as being mild in May, but cold in June at Churchill. The York record has only six days of temperatures for June, but May is distinctly above average 2.4°C (-2.0°C).

(f) February 1831 was reported as mild. This was probably due to a high percentage of south winds (30%). The mean monthly temperature was -19.5°C (-27°C).

(g) June 1842 is mentioned as being very cold in the written record. The measured average was 2.6°C (5.8°C).

(h) Written comments for 1849 read: "Very late Fall. Interior rivers and lakes unfrozen until the 10th of December." The temperature record supports these comments, for the November average was -5.8°C (-12.4°C).

(i) During the period from 1841 to 1852 summer temperatures remained consistent and close to the modern average (July 12.6°C). Winter temperatures show a gradual increase through the same time.

CONCLUSION

I have examined here one of the earliest and most extensive temperature records in North America - certainly the earliest in central Canada. The accuracy of the records has been tested and an outline of the significant features provides insight into temperature trends in the latter half of the eighteenth century, and the nineteenth century. These records are remarkable. Undoubtedly they will be prized more highly as they become better known.

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TREE-RING DATING OF DRIFTWOOD FROM RAISED BEACHES ON THE HUDSON BAY COAST

M.L. Parker,[1] Paul A. Bramhall[2] and Sandra G. Johnson[2]

INTRODUCTION

A better understanding of present and future climate can be achieved by examination of climatic conditions that have prevailed in the past. In many parts of North America, trees have lived for a longer period of time than man has kept meteorological records. Weather records can be extended, in a proxy manner, by using tree-ring data. This report is designed to do so for an area on the west coast of Hudson Bay near Churchill, Manitoba.

This study is part of a larger research project entitled "Dendroclimatic Investigations in Canada" that has been in progress for the past eight years, first at the Western Forest Products Laboratory, Canadian Forestry Service, and then at Forintek Canada Corporation. Within this broader context, specific areas of study, with respect to both subject matter and geographic location have varied considerably. However, the general goals have been to investigate the relationships between tree growth (in the form of tree-ring width and density) and climatic factors.

The technique of x-ray densitometry of wood has become an important tool in dendrochronological and wood science research because it provides data that are highly correlated with climatic and environmental conditions. Different species of trees, and trees growing in different environments, respond differently to regional climatic factors. The nature of annual ring parameters such as earlywood width, latewood width, latewood density, etc., are also dependent on climatic variables. The purpose of this study is to relate these tree-ring variables, as determined by x-ray densitometry, to climatic factors as a basis for more precisely defining these relationships. Ultimately, this approach is expected to devise models which will provide more accurate historic reconstructions of past climatic conditions. This may lead to a better understanding of potential future fluctuations in climate, and an understanding of how climate may affect future wood production, agricultural production and other economically-significant climatically-related factors.

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Long tree-ring chronologies are more valuable than short ones for reconstructing climatic history or providing a basis for dating archaeological or other tree-ring material. The trees in the Hudson Bay area do not generally attain great age. Therefore, in order to build long tree-ring chronologies, it is necessary to extend the living-tree records by dating dead-wood samples.

Raised beaches were formed in the area south of Churchill as long as 9,000 years ago, and have been formed periodically from that time to the present (Fairbridge 1979). Although ancient wood probably does not exist on the surface of the older of these beaches, buried wood may well be preserved in the permafrost. Driftwood does exist, however, on the surface of younger raised beaches near the present shoreline of Hudson Bay. One of the major goals of this project, in order to determine the potential for tree-ring studies, has been to observe just how far inland driftwood can be found, and to collect and to attempt to date that wood by dendrochronological techniques. This serves several purposes, in that information can be obtained about the nature of the beaches and the driftwood, and proxy climatic data can be derived from resultant tree-ring chronologies built from this old wood.

Field work was conducted over a three-week period in August 1981. During 1982, this study has continued with samples collected from the Churchill area. The area of investigation extended from Churchill to York Factory, Manitoba along the coast of Hudson Bay and over an area from the present coast to approximately 150 km inland.

The work performed on this project has four parts: (1) building tree-ring width and density chronologies from living-tree wood samples; (2) searching for driftwood on the raised beaches; (3) collecting and dating the driftwood and building tree-ring chronologies of the annual rings in these samples; and (4) relating these tree-ring data to local meteorological records.

1. The Churchill River Living-Tree Black Spruce Site

A search was made, from the air, of the forested area near Churchill for an appropriate site from which to obtain the living-tree samples. A site was selected which is located approximately 65 km up the Churchill River from its mouth and about 5 km west of the river. Disks were collected and tree-ring width and density chronologies were built from samples of 12 black spruce (*Picea mariana* (Mill.) BSP.) trees. The chronologies produced extend from 1870 to 1981.

2. Search for Driftwood from the Air

An extensive search was made by air between Churchill and York Factory extending inland about 150 km. Driftwood was seen on raised beaches up to about 10 km from the present shore.

3. The Owl River Driftwood Site

The area located with the greatest concentration of driftwood was on the raised beaches near the mouth of Owl River, approximately halfway between Churchill and York Factory. The age of the raised beaches increases with the distance from the present shoreline of Hudson Bay. Forty-eight driftwood samples were collected from six of the ten raised beaches that extend inland 1.7 km from the present shoreline. Species identification was carried out for all samples. Thirty samples were processed in the x-ray densitometry system at Forintek Canada Corporation. Eighteen samples were not processed, either because they had too few rings, were too decomposed, or contained very compressed, narrow ring series. A computer crossdating technique was employed in an attempt to crossdate the driftwood samples with Churchill River living-tree chronologies and with a maximum ring density chronology derived from Cri Lake (near Great Whale River, Québec), about 965 km away, on the opposite side of Hudson Bay. Four driftwood samples, collected in 1979, from the present beach at Churchill, also were processed with the Owl River driftwood.

4. Comparison of Tree-Ring Data and Weather Records

Data from individual trees from the Churchill River black spruce site, were averaged to produce composite ring width and maximum ring density chronologies. These chronologies were correlated with total monthly precipitation and mean monthly temperature records from Churchill. Although the quality of tree-ring series derived from trees in this area is not exceptionally good, the results of this study are encouraging. Dendrochronological dates were obtained from many of the driftwood samples; the tree-ring chronologies crossdated well over long distances; and the tree-ring parameters correlate fairly well with climatic factors.

LITERATURE REVIEW

The techniques of x-ray densitometry and computer crossdating as employed in Ottawa (Parker 1969A, 1969B, 1970A, 1970B; Parker and Henoch 1969, 1971; Jones and Parker 1970; Parker and Meleskie 1970) and in Vancouver (Parker 1972, 1976; Parker and Jozsa 1973A, 1973B, 1977A, 1977B; Parker and Kennedy 1973; Parker *et al.* 1973A, 1973B, 1974A, 1974B, 1976, 1977, 1979, 1980, 1981; Heger *et al.* 1974) have been described previously. The highest correlations obtained between tree-ring variables and weather factors were: between maximum ring density and August temperature for Engelmann spruce (*Picea engelmanni* Parry) in the Rocky Mountains (Parker and Henoch 1971); for white spruce (*Picea glauca* (Moench) Voss) in the Mackenzie Delta (Parker 1976); and for white spruce in Québec (Parker *et al.* 1981).

Ritchie (1957) has reported on forest vegetation in the Churchill area with special attention to the sequence of vegetation after emergence. Some information relating to the age and location of living trees that are potentially good for building tree-ring chronologies is given in this report.

During the last (Wisconsin) glaciation, ice in the Hudson Bay area reached a thickness of about 2000 m (Fairbridge 1979). The Laurentide ice sheet began to retreat in northern Canada about 13,000 years ago and the ice finally disappeared from the Hudson Bay area about 7,000 years ago (Craig 1969). As the Wisconsin ice sheets melted, sea level rose. As the load of glacial ice which had depressed the earth's crust, melted, the land in the Hudson

Bay area rose faster than the sea. This uplift of land changed the location of the shoreline and created the raised beaches. Although this subject is complex and extensive, it is sufficient to note that there is a progression in age of the raised beaches away from the present shoreline; the youngest beaches occur near the shore and their age increases progressively with increasing distance from the shore of Hudson Bay.

FIELD COLLECTING

Background

Field work was conducted over a three-week period beginning on August 10, 1981. The two main sampling locations were the Churchill River black spruce living-tree site and the Owl River driftwood site (Figures 1 and 2).

Other field work consisted of a search, by air, for driftwood on raised beaches between Churchill and York Factory, and an examination of the larger remaining Hudson's Bay Company structure at York Factory to determine the possible usefulness of timbers in that building for dendrochronological purposes. Also, four driftwood samples collected in June 1979 from the present beach at Churchill, directly north of the graveyard, were examined (Figure 3).

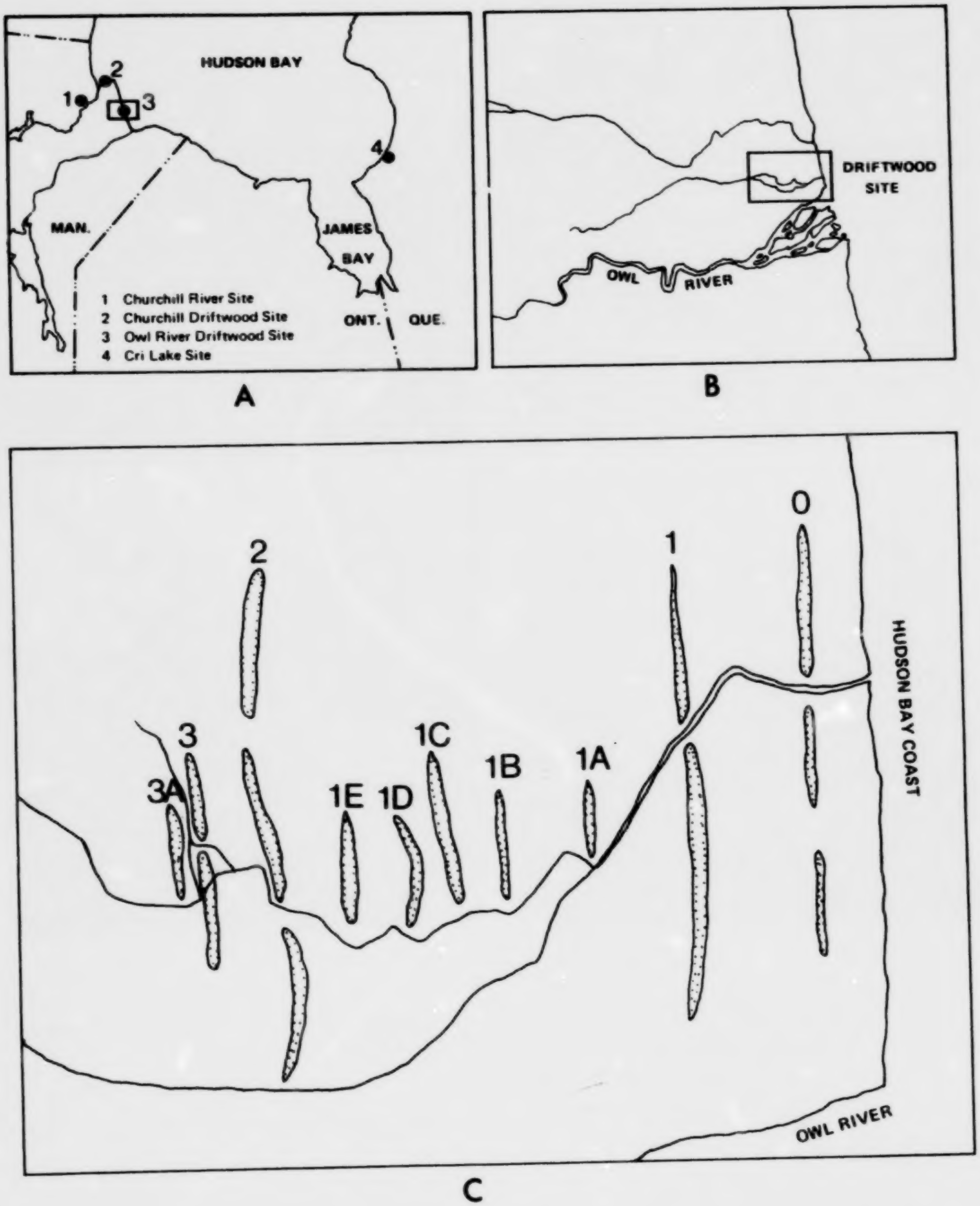
Churchill River Living-Tree Site

Samples were collected here on August 17, 1981 by M.L. Parker and Douglas Webber. The site is approximately 65 km up the Churchill River from its mouth and about 5 km west of the river (Figure 1). The terrain consists of raised beaches, peat bogs, black spruce and tamarack (*Larix laricina* (Du Roi) K. Koch) forest cover and numerous lakes.

Trees were felled and disks were taken from 13 living black spruce trees, one dead black spruce snag, and two living tamarack trees. The form of the trees and the nature of the surrounding terrain are illustrated in Figure 2.

Owl River Driftwood

After an extensive search for driftwood on raised beaches between Churchill and York Factory, it was decided to collect wood on the north side of Owl River near its mouth


HUDSON BAY
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2 Churchill Driftwood Site
3 Owl River Driftwood Site
4 Cri Lake Site
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DRIFTWOOD
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3A
1E
1D
1C
1B
1A
HUDSON BAY COAST
OWL RIVER
C

FIGURE 1: *A. General area, living-tree and driftwood sites.*

B. Location of the Owl River driftwood site.

C. Raised beaches at the Owl River driftwood site.

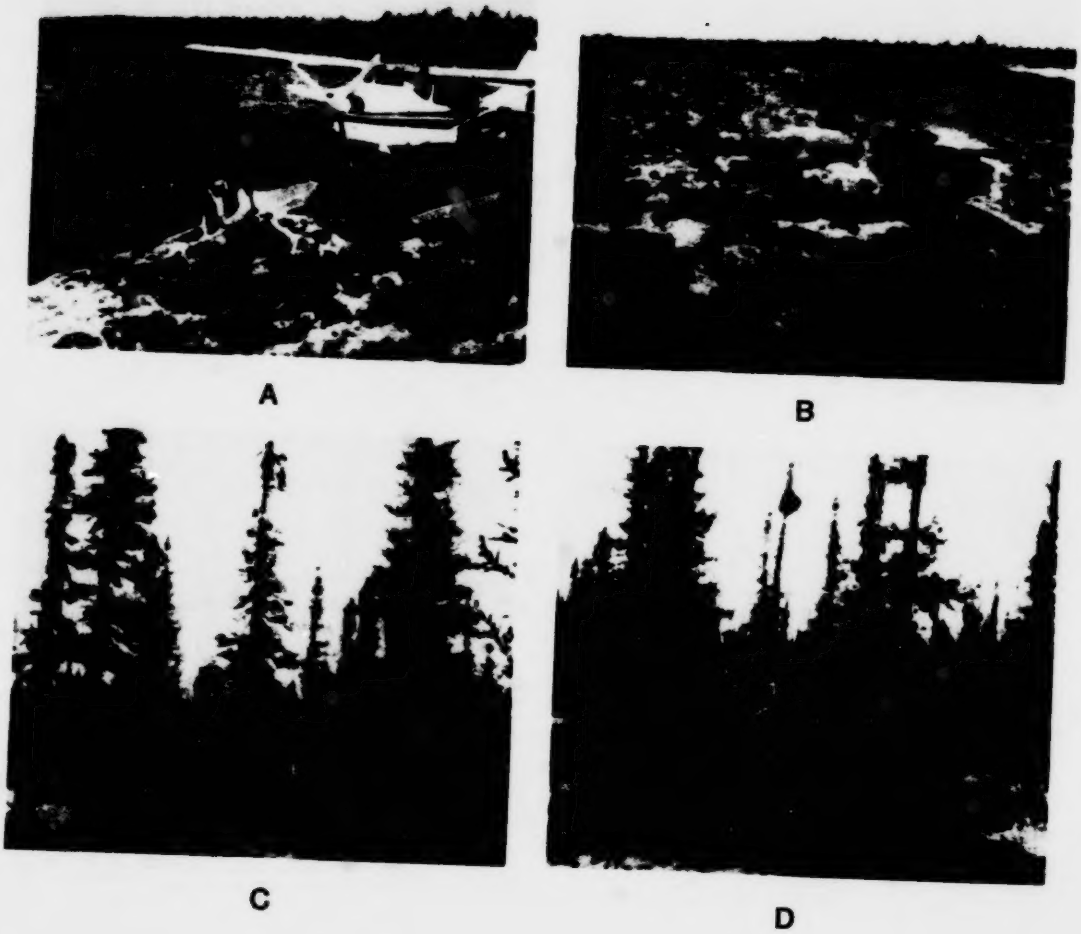


FIGURE 2: *Churchill River Black Spruce Site.*

A. The black spruce site is located on the far side of the lake. The pilot, Douglas Webber is on a peat bog that is typical of the area.

B. The peat bog, looking south.

C. Tree CR-1; 7.2 m tall, sample taken 0.60-0.71 m above ground.

D. Tree CR-2; 6.4 m tall, sample taken 0.23-0.40 m above ground.

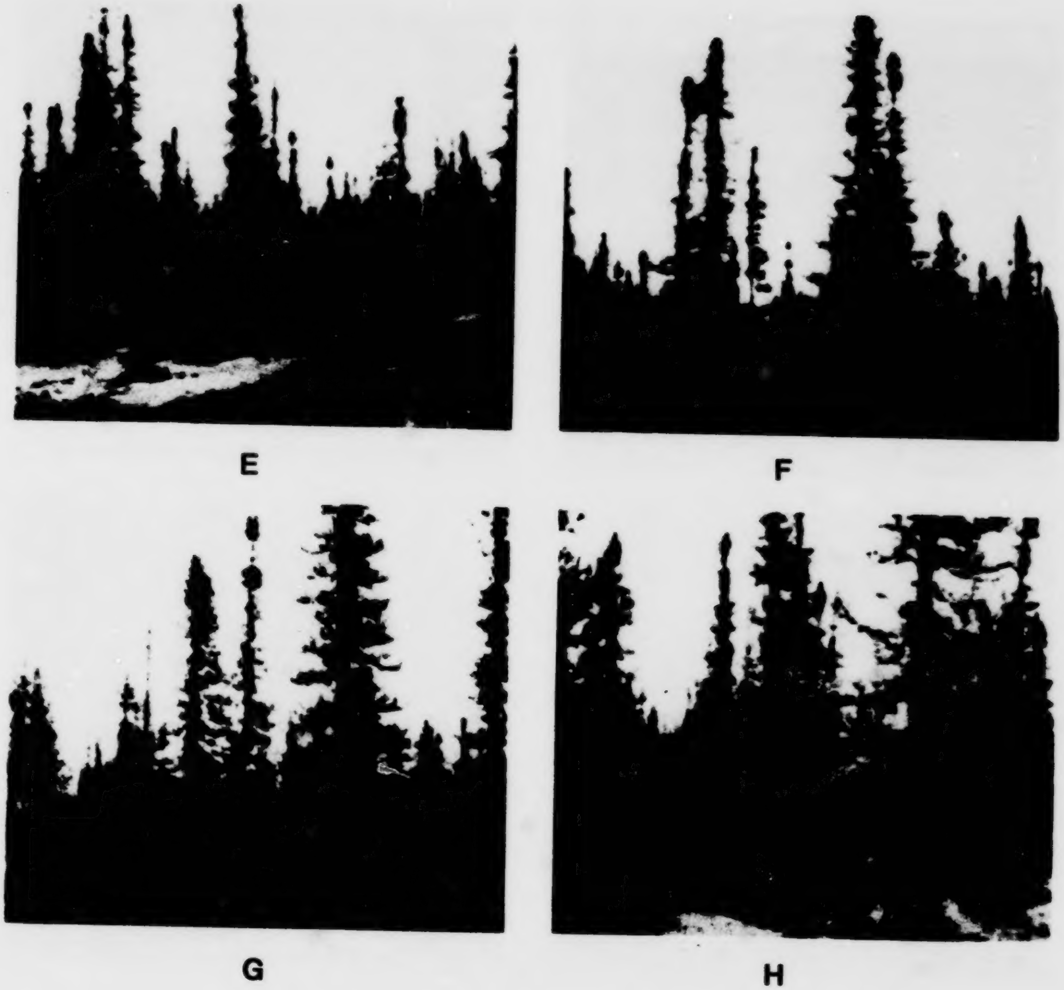


FIGURE 2: *Churchill River Black Spruce Site.*

E. Tree CR-3; 6.7 m tall, sample taken 0.20-0.40 m above ground.

F. Tree CR-4; 6.2 m tall, sample taken 0.20-0.38 m above ground.

G. Tree CR-5; 8.5 m tall, sample taken 0.38-0.54 m above ground.

H. Tree CR-6; 7.5 m tall, sample taken 0.25-0.50 m above ground.

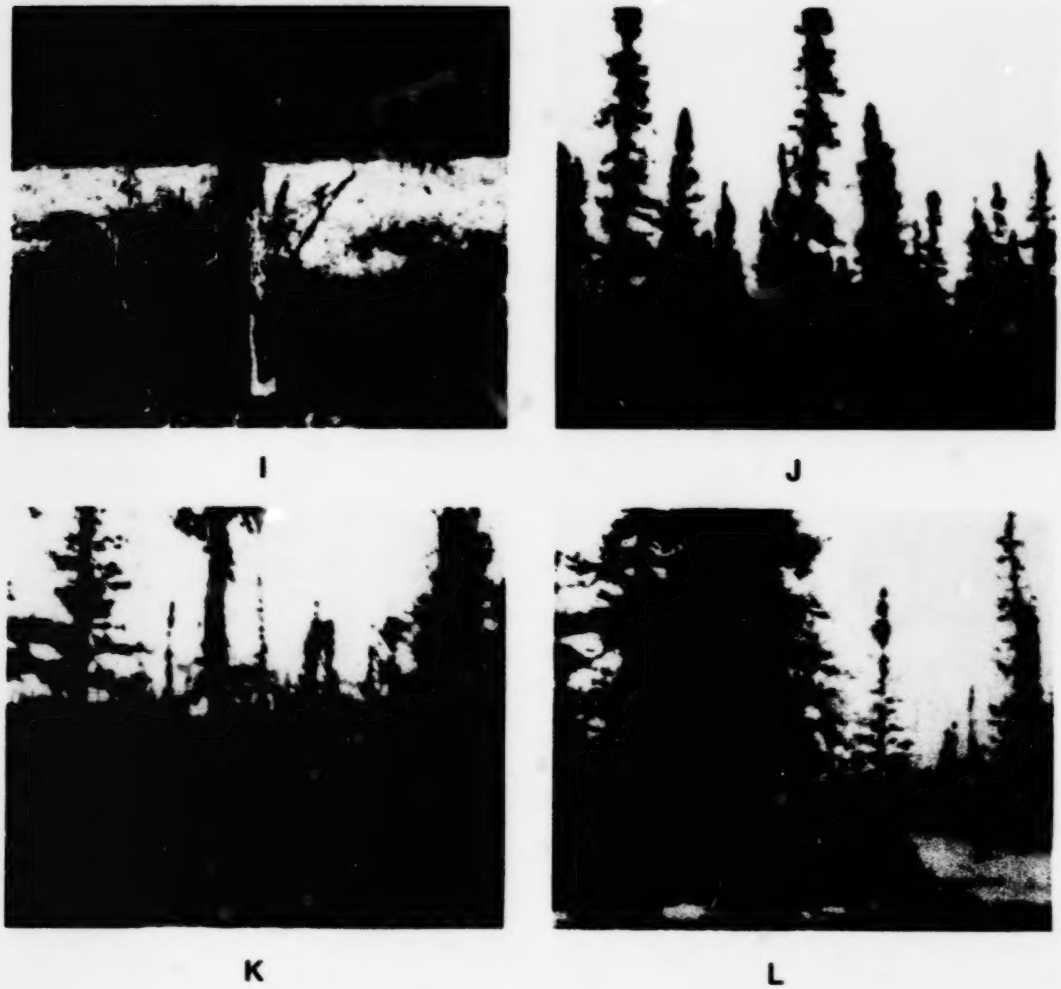


FIGURE 2: *Churchill River Black Spruce Site.*

I. Tree CR-7; 8.8 m tall, sample taken 0.40-0.55 m above ground.

J. Tree CR-8; 8.7 m tall, sample taken 0.22-0.39 m above ground.

K. Tree CR-9; 7 m tall, sample taken 0.83-0.90 m above ground.

L. Tree CR-10; 8.4 m tall, sample taken 0.26-0.40 m above ground.

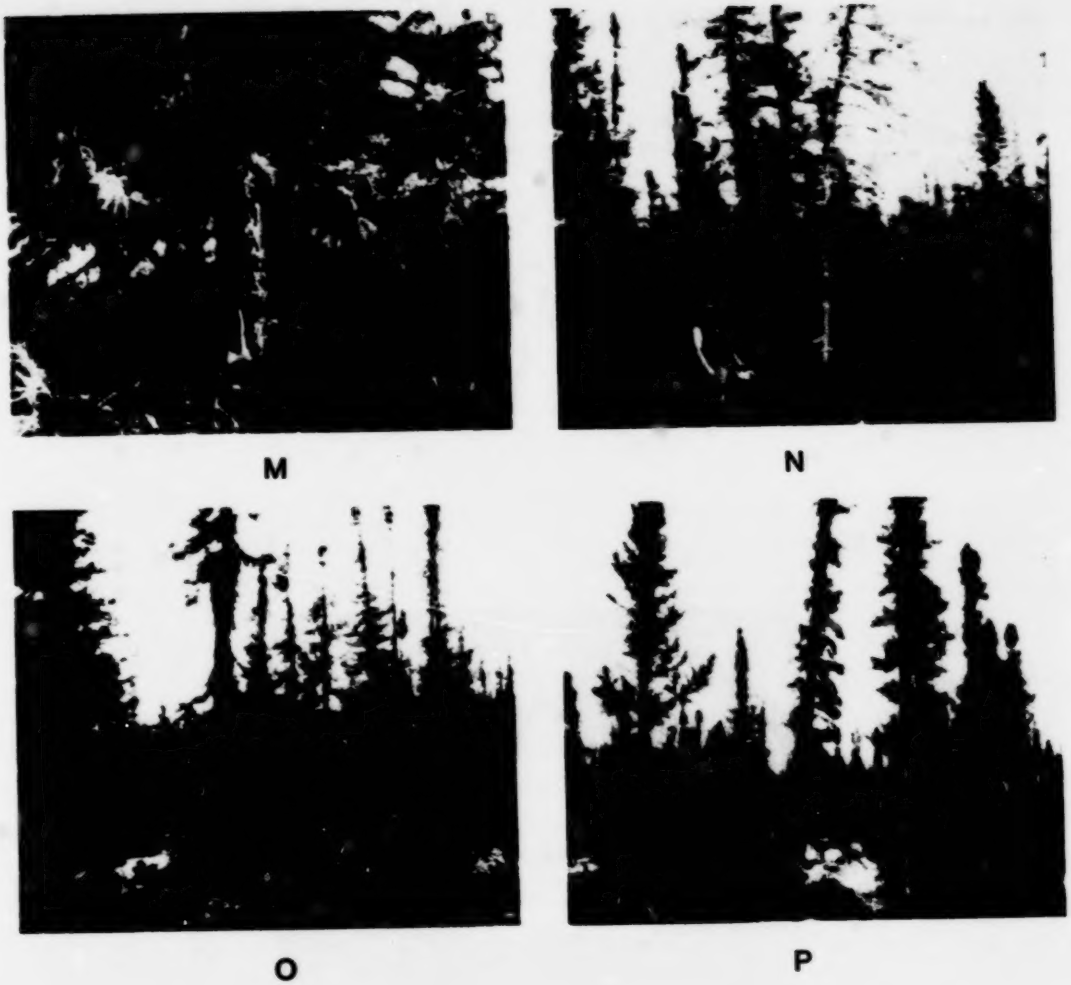


FIGURE 2: *Churchill River Black Spruce Site.*

M. Tree CR-11: 10.7 m tall, sample taken 0.50-0.56 m above ground.

Tree CR-12; (behind CR-11) 7.9 m tall, sample taken 0.30-0.35 m above ground.

Tree CR-13; (behind CR-11) 9.1 m tall, sample taken 0.45-0.50 m above ground.

N. Tree CR-14; 7.5 m tall, sample taken 0.18-0.32 m above ground.

Tree CR-15; 9.2 m tall, sample taken 0.12-0.32 m above ground.

O. Tree CR-16; rotten snag, sample taken 1.46-1.7 m above ground but not used in chronology building.

P. Example of tree with rotten centre that was not collected.

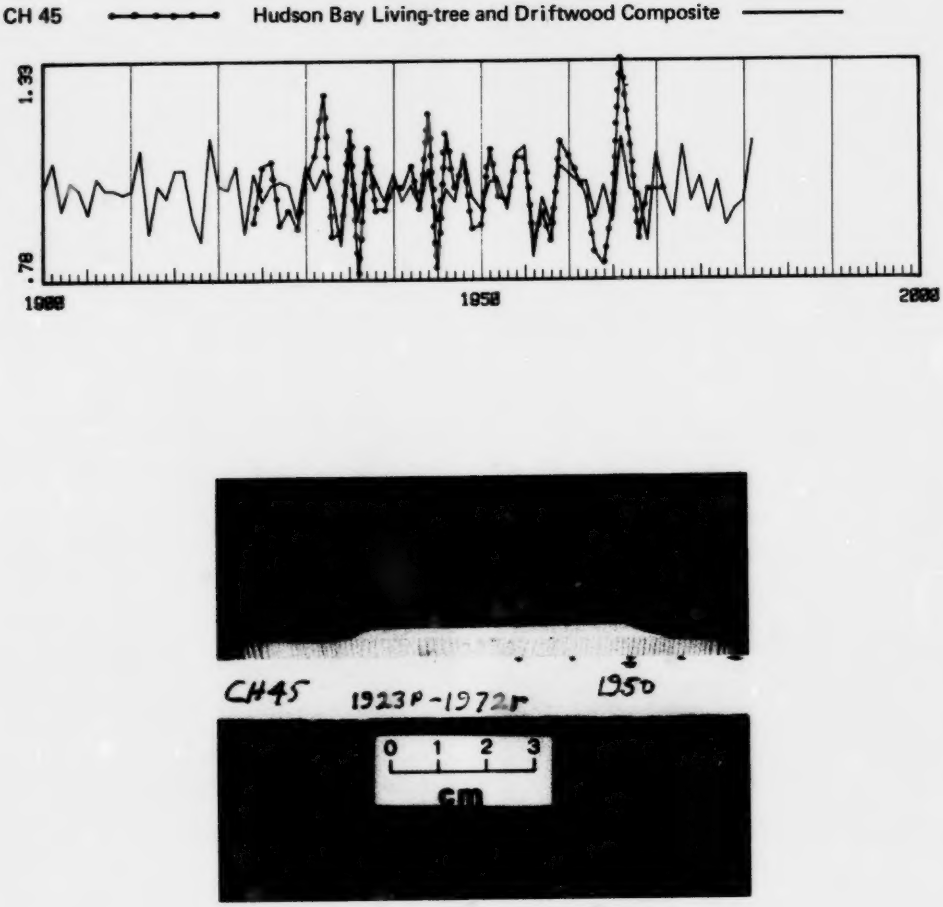


FIGURE 3: *Dated Churchill driftwood sample.*

(Figures 1 and 4). Only at this site was driftwood located on the raised beaches where a small airplane on floats could be landed.

The driftwood samples were collected by M.L. Parker and Steven Bruce. Disks were cut from the driftwood with a chain saw or a bow saw. Forty-eight driftwood samples were collected from six of the ten raised beaches that extend inland 1.7 km from the present shoreline (Figures 4 and 5).

LABORATORY PROCESSING

X-Ray Densitometry

Ring-width and ring-density data were derived from the tree-ring samples using x-ray densitometry. This method is relatively new to dendrochronology, and was pioneered in France by Hubert Polge (1963, 1966). The techniques and instruments of x-ray densitometry used at the Forintek Canada Western Laboratory are briefly:

(1) tree-ring samples, in the form of increment cores or radial strips from disks, are air dried and glued between two mounting sticks;

(2) these samples are cut to a uniform thickness on a twin-blade saw built for this purpose;

(3) samples are labelled with x-ray opaque paint;

(4) a portion of one of the mounting sticks is cut away and the cell angle (the angle formed by the long axis of the longitudinal tracheid cells and the long axis of the increment core) is measured under a microscope;

(5) prepared samples are placed on a sheet of x-ray film along with calibration wedges, and exposed at the proper angle by a moving x-ray machine;

(6) x-ray film is developed under carefully controlled conditions;

(7) the radiograph is then examined on a light table under a low-power microscope, and annual rings are arbitrarily numbered or marked with calendar-year dates;

(8) radiographs are then scanned on a computerized densitometer that converts the image of the tree-ring sample into ring-width and ring-density data;

(9) data are stored on magnetic tape for further processing and summarizing.

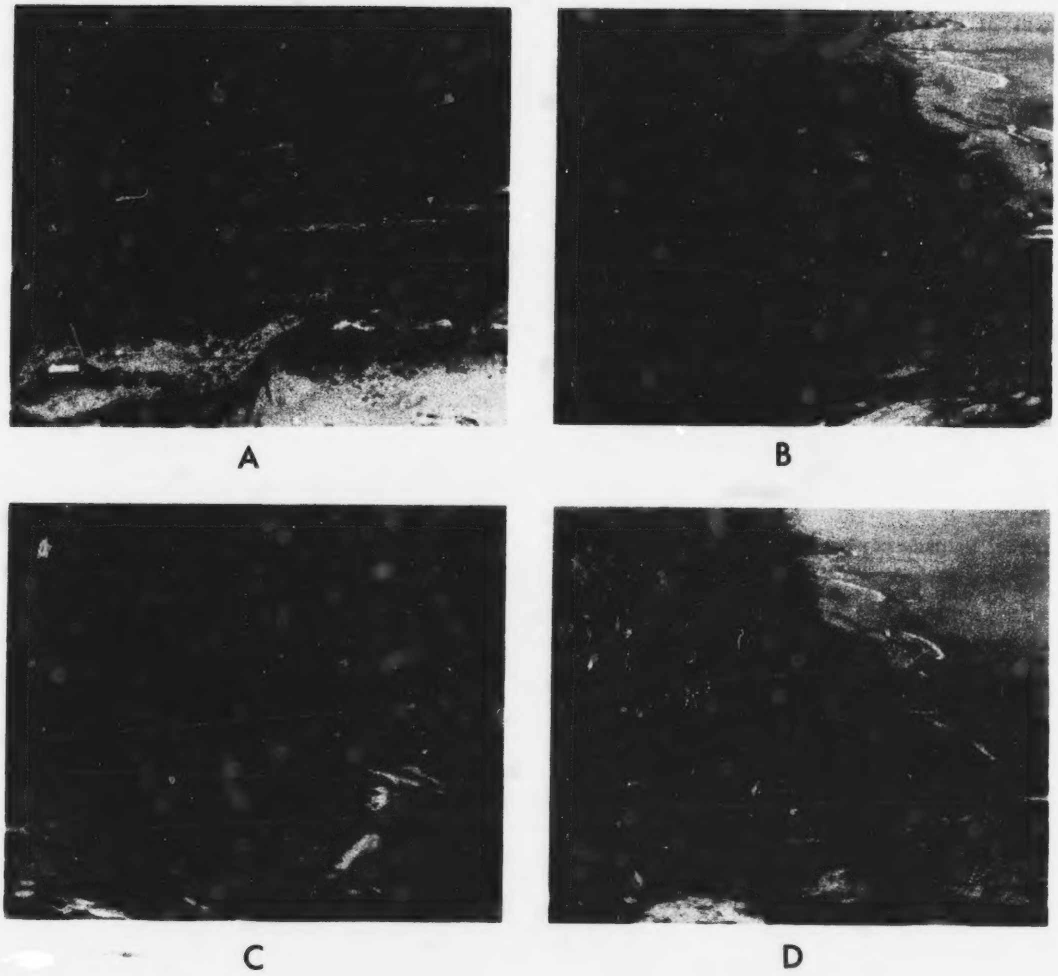


FIGURE 4: *The Owl River driftwood site from the air. A. Looking west. B. Looking north. C. Looking northwest. D. Looking north and showing the mouth of Owl River.*

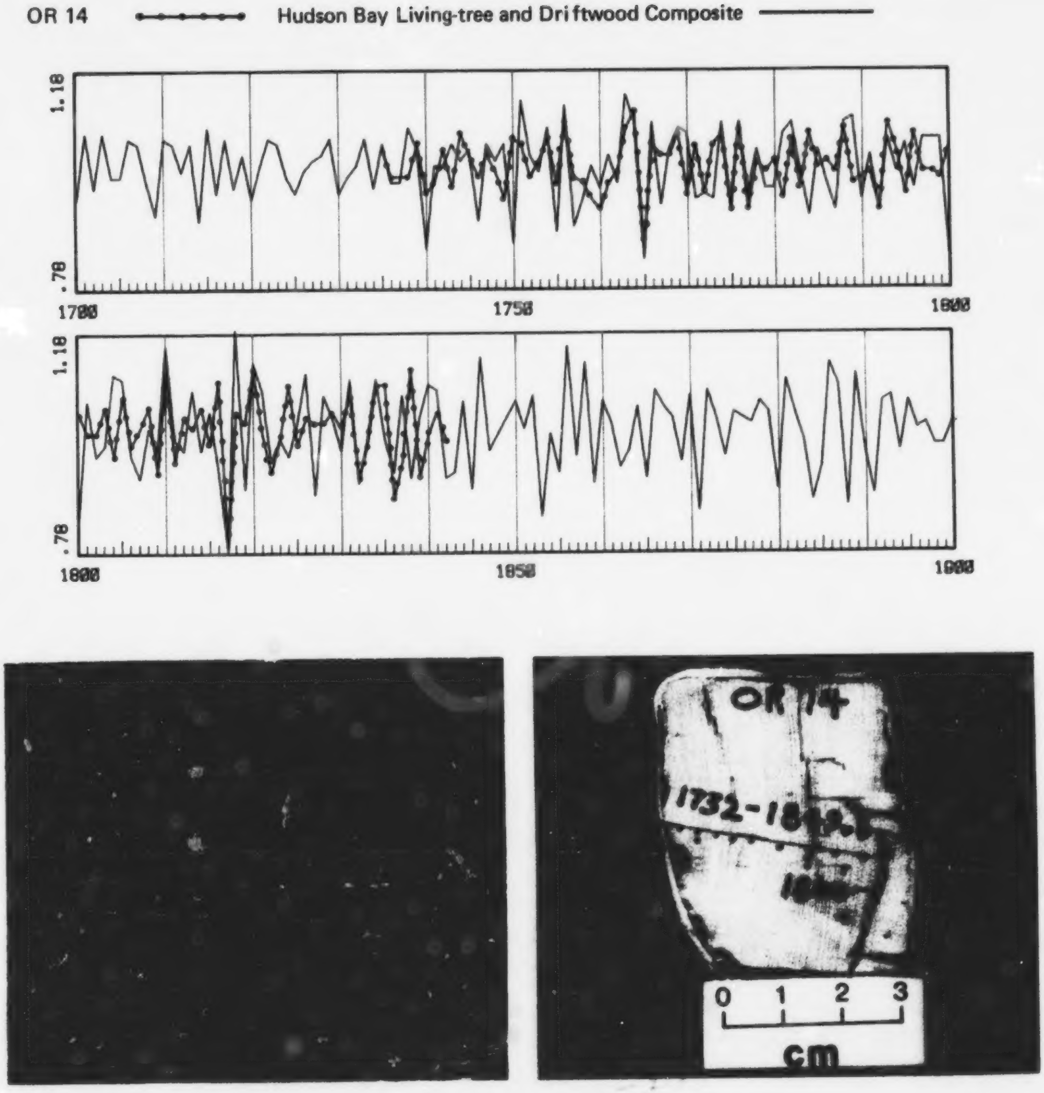


FIGURE 5A: *Dated Owl River driftwood sample (OR 14).*

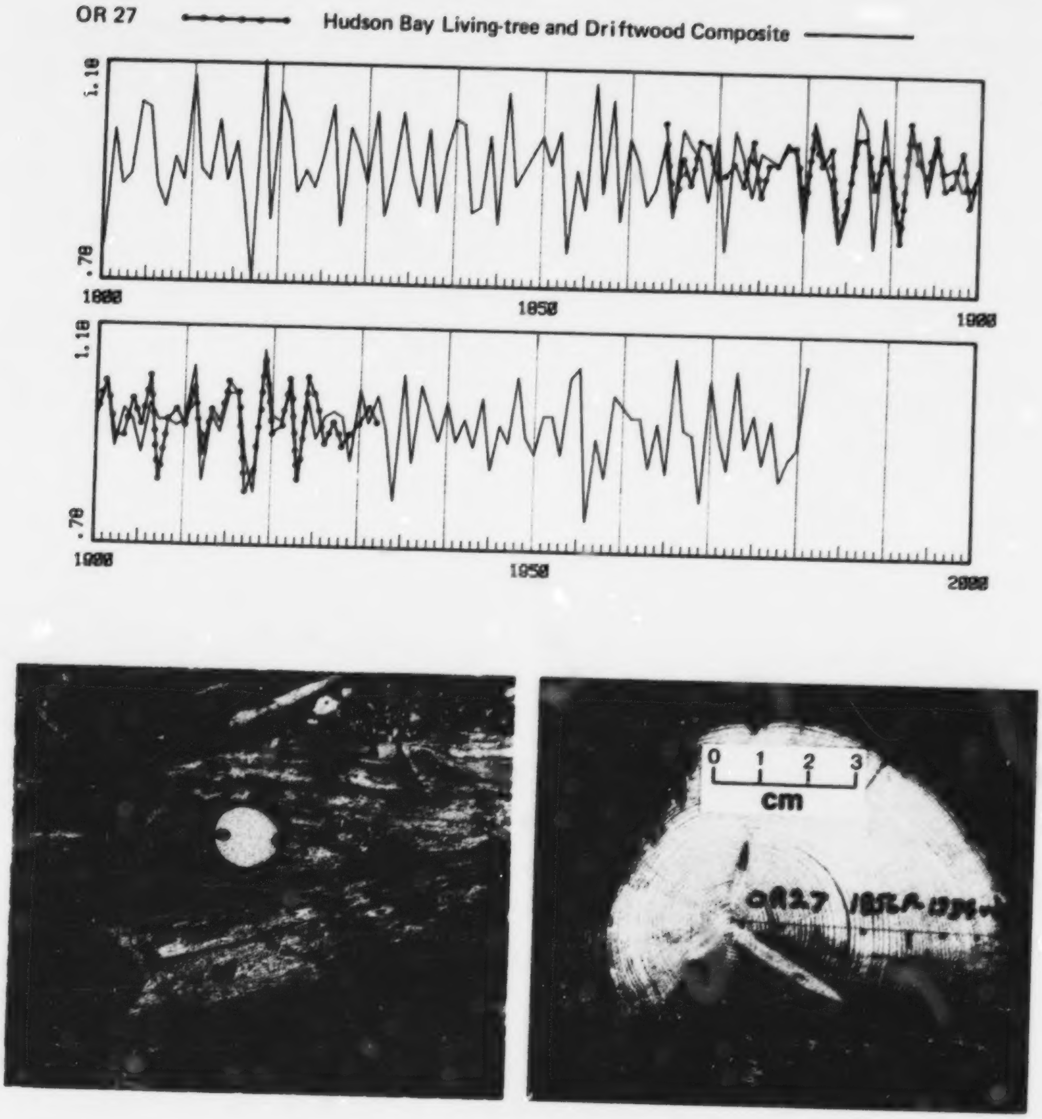


FIGURE 5B: *Dated Owl River driftwood sample (OR 27).*

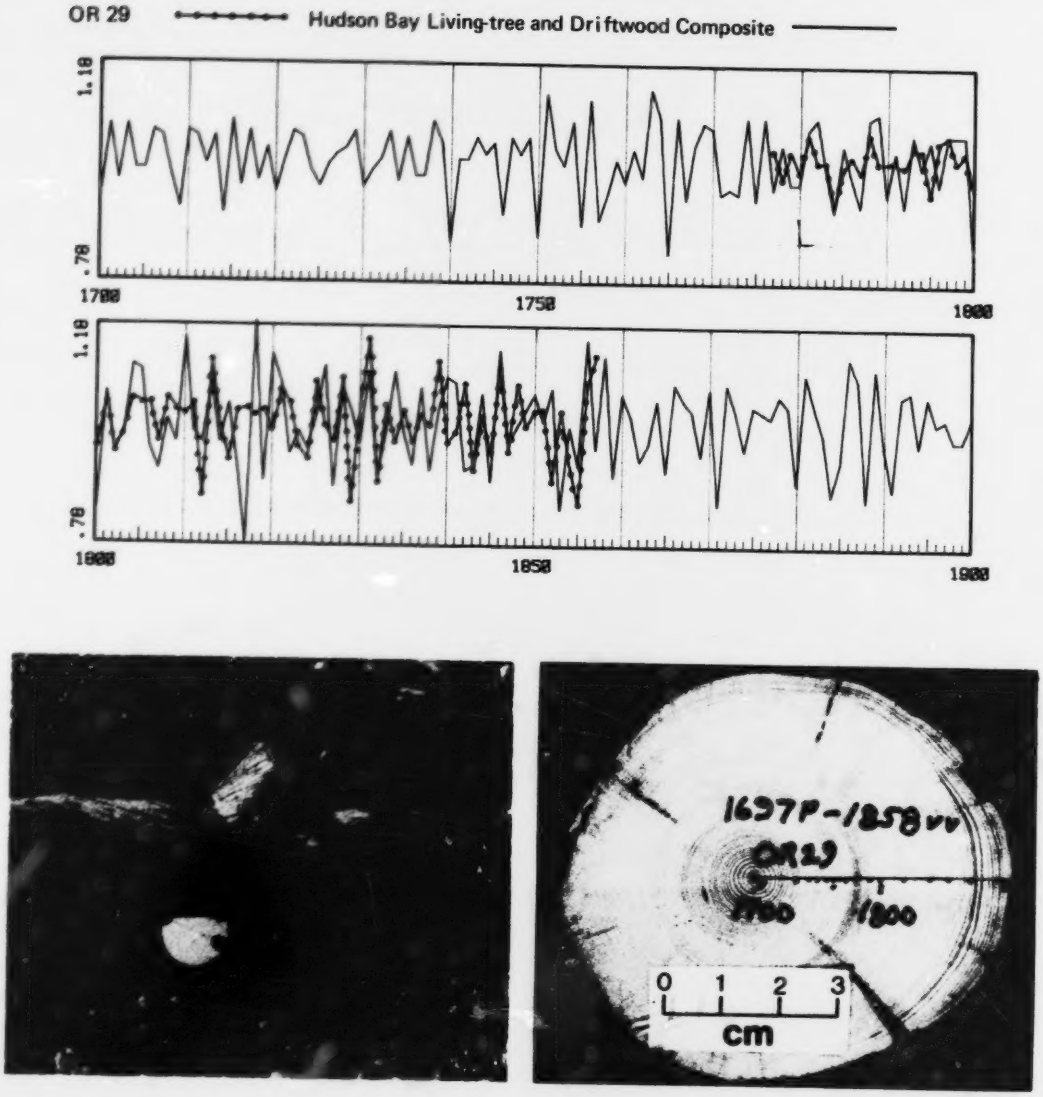


FIGURE 5C: *Dated Owl River driftwood sample (OR 29).*

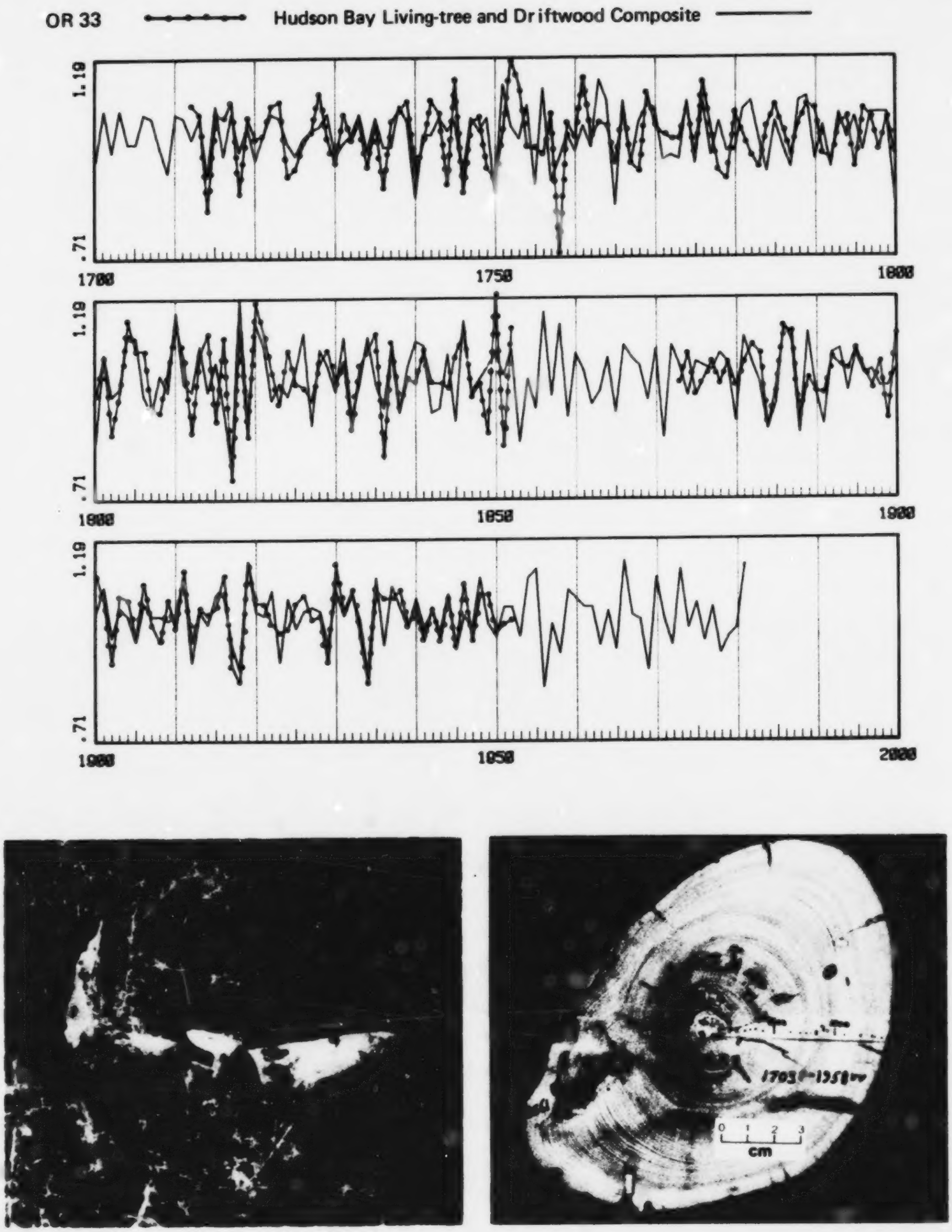
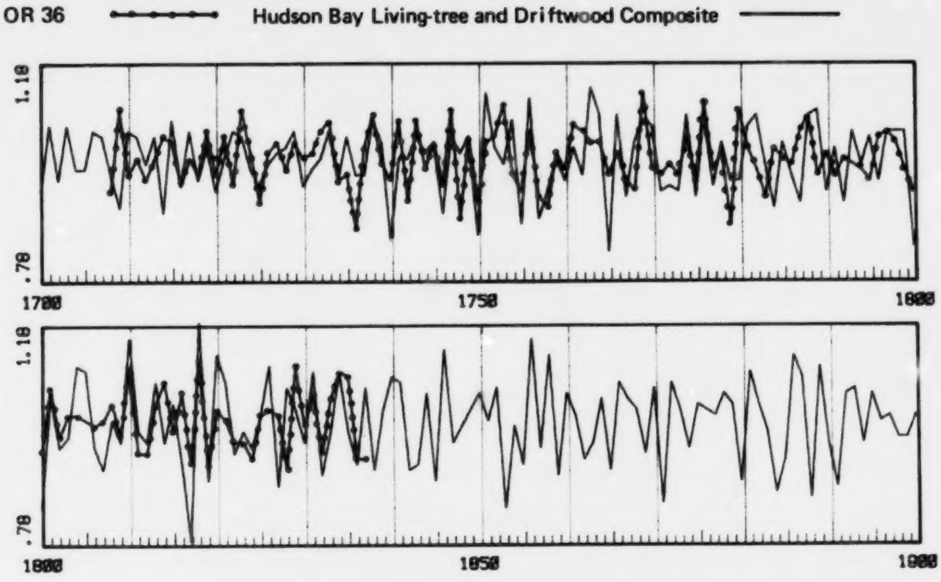


FIGURE 5D: *Dated Owl River driftwood sample (OR 33).*



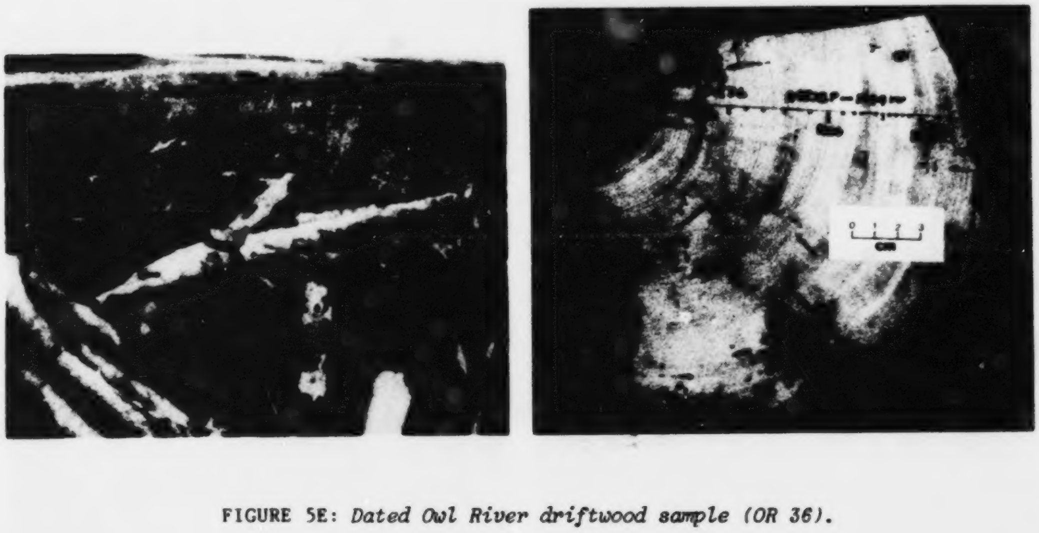


FIGURE 5E: *Dated Owl River driftwood sample (OR 36).*

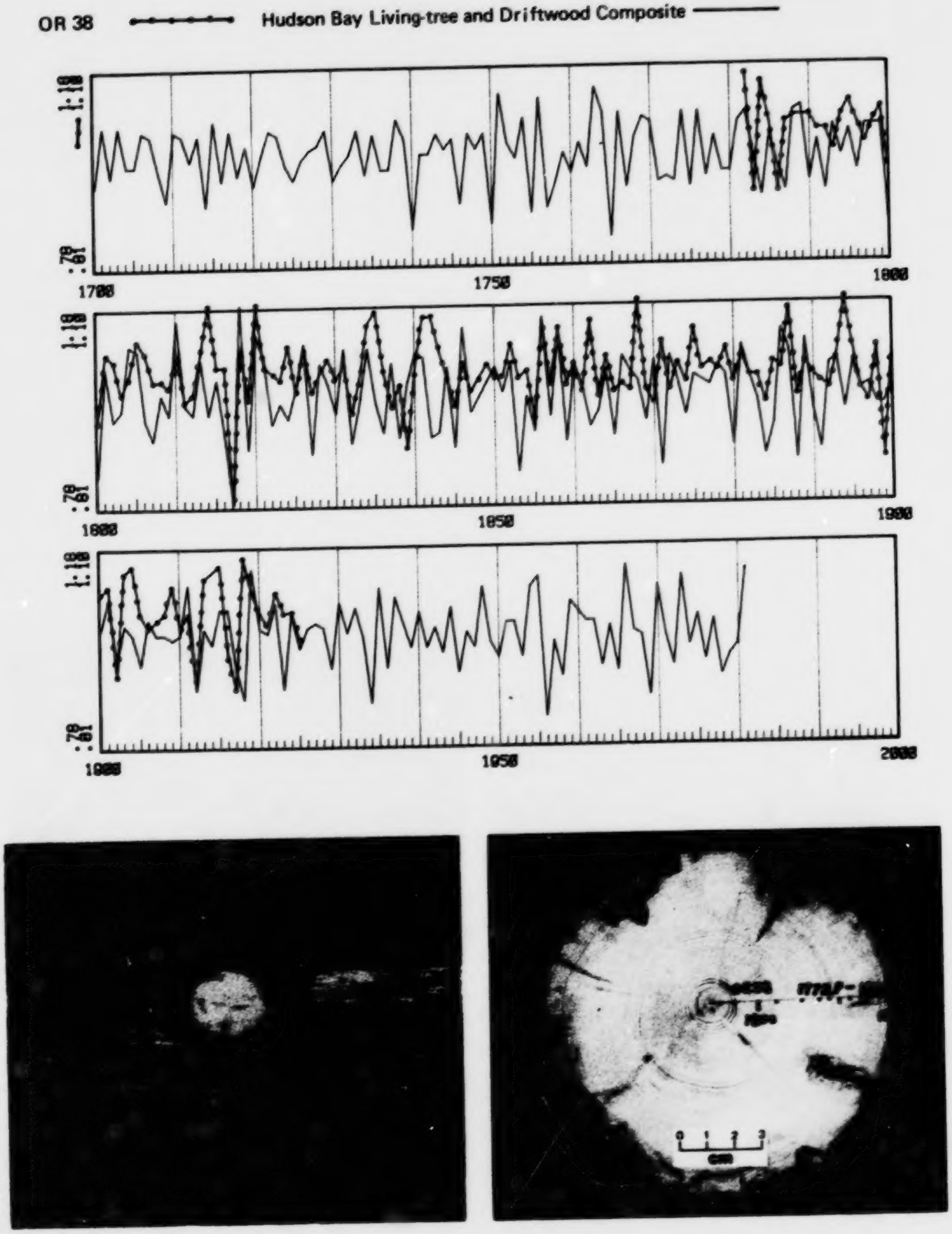


FIGURE 5F: *Dated Owl River driftwood sample (OR 38).*

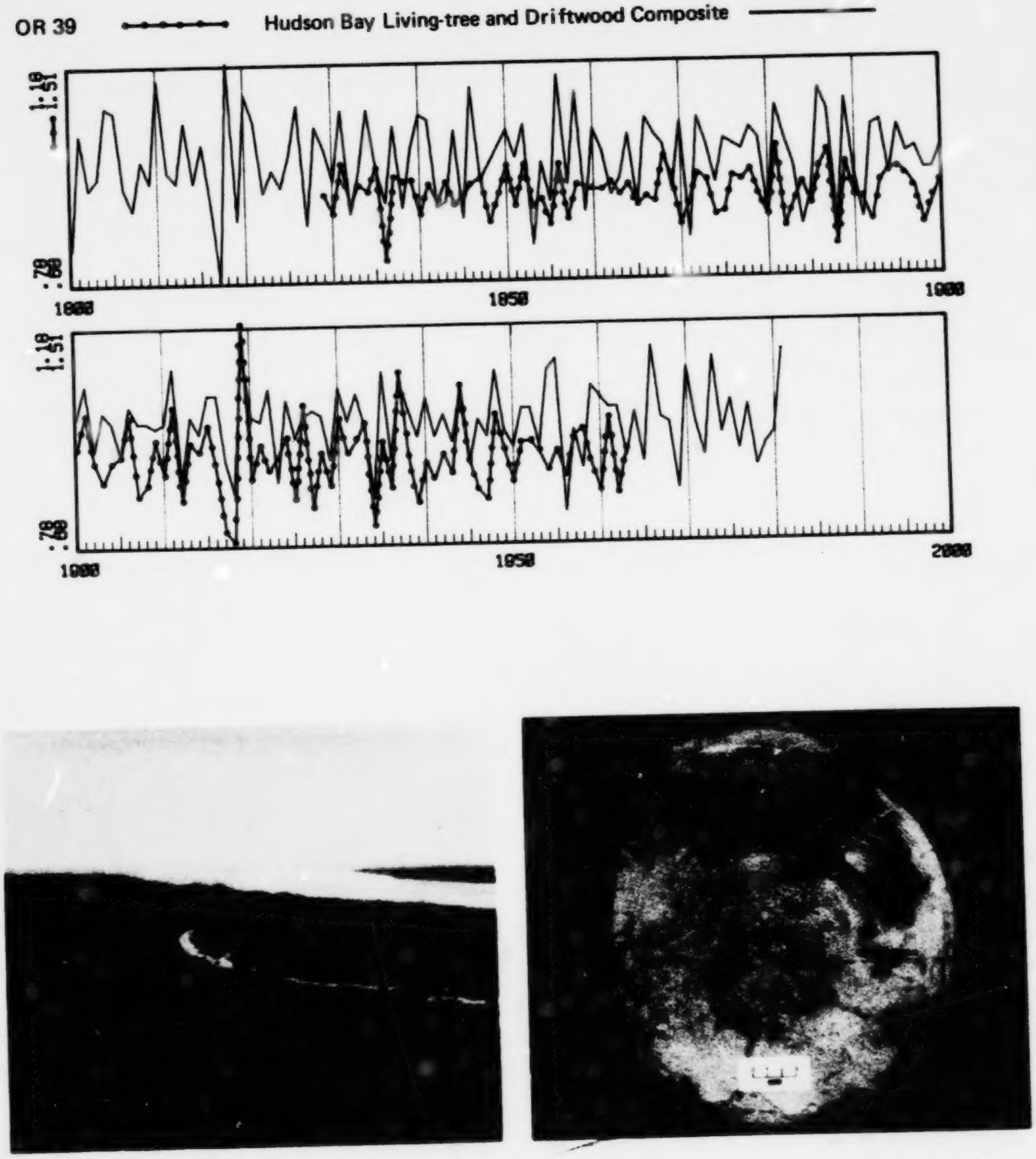
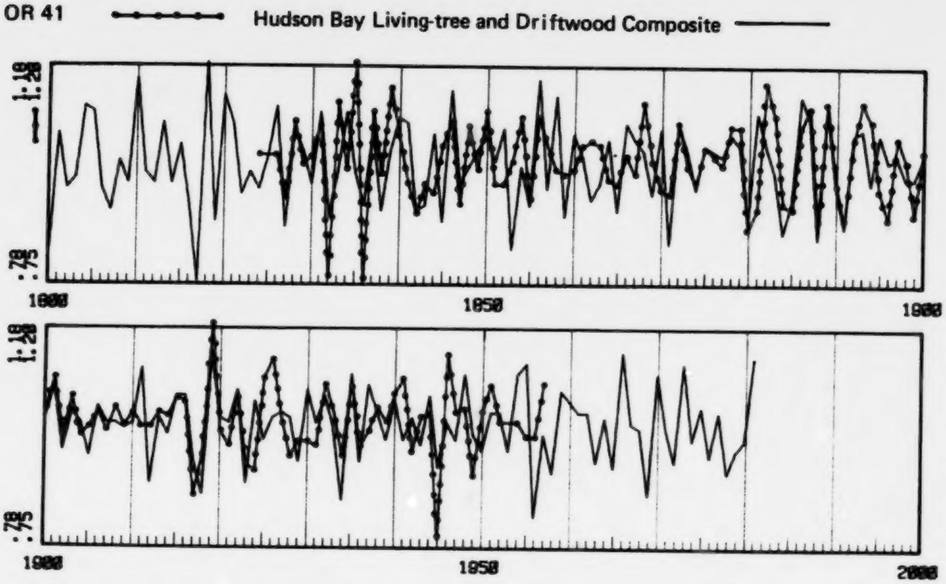


FIGURE 5G: *Dated Owl River driftwood sample (OR 39).*



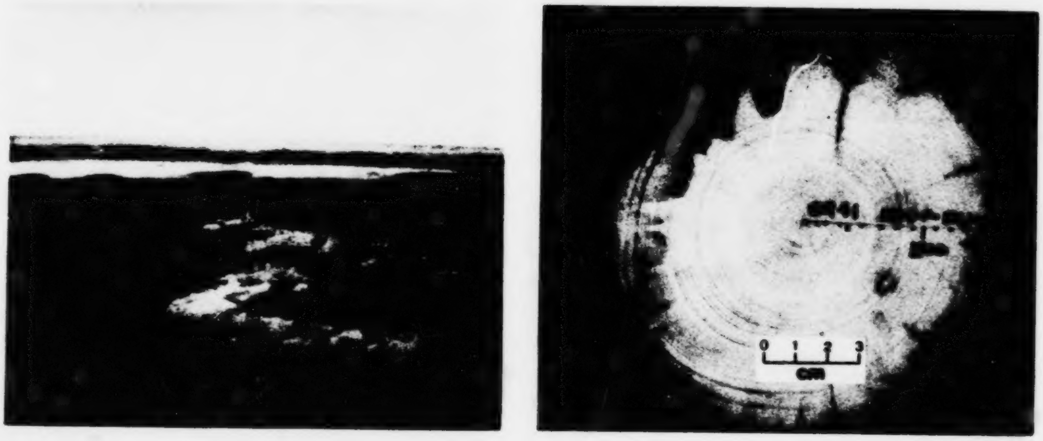

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FIGURE 5H: *Dated Owl River driftwood sample (OR 41).*

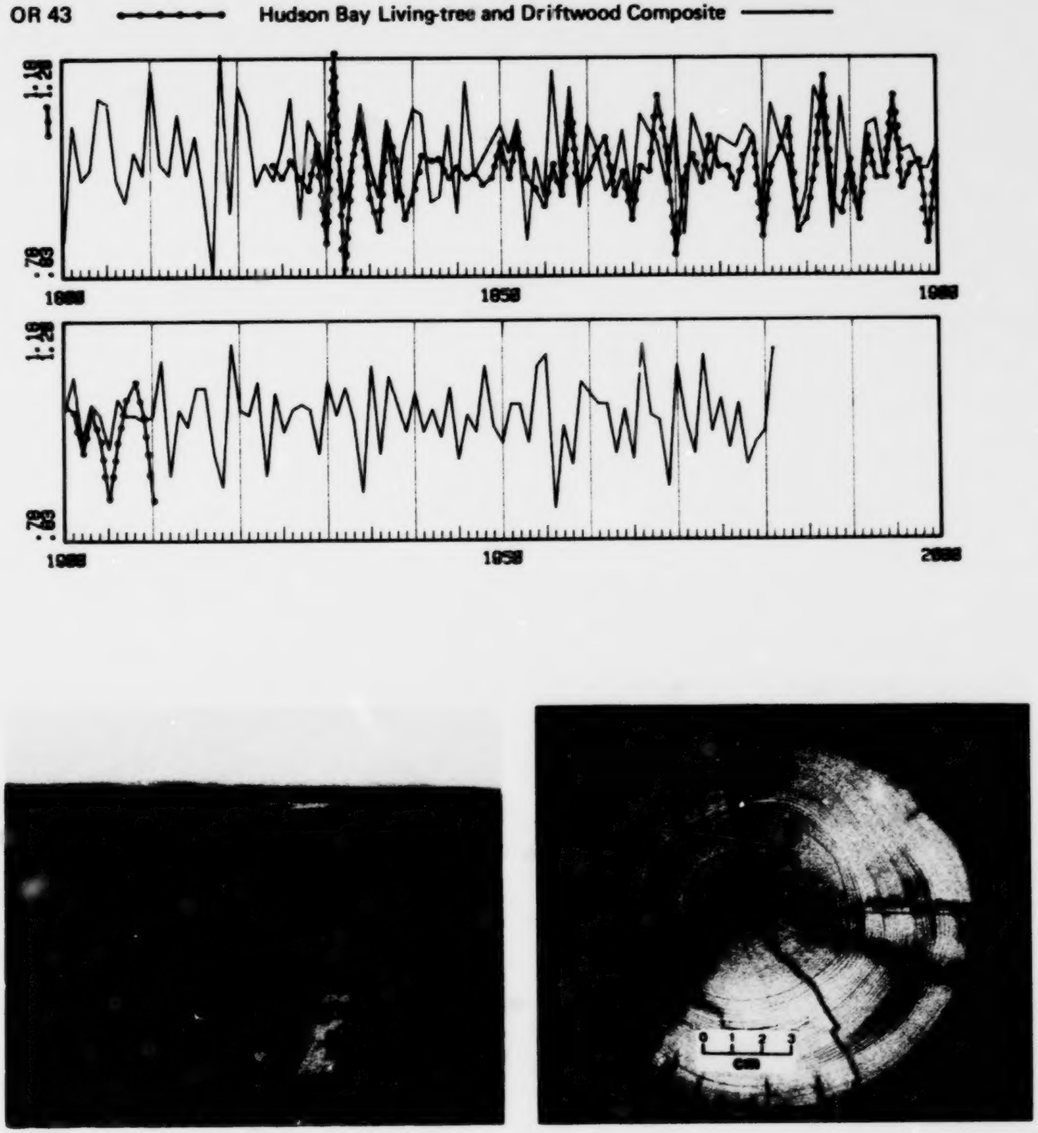


FIGURE 51: *Dated Owl River driftwood sample (OR 43; in distance at left).*

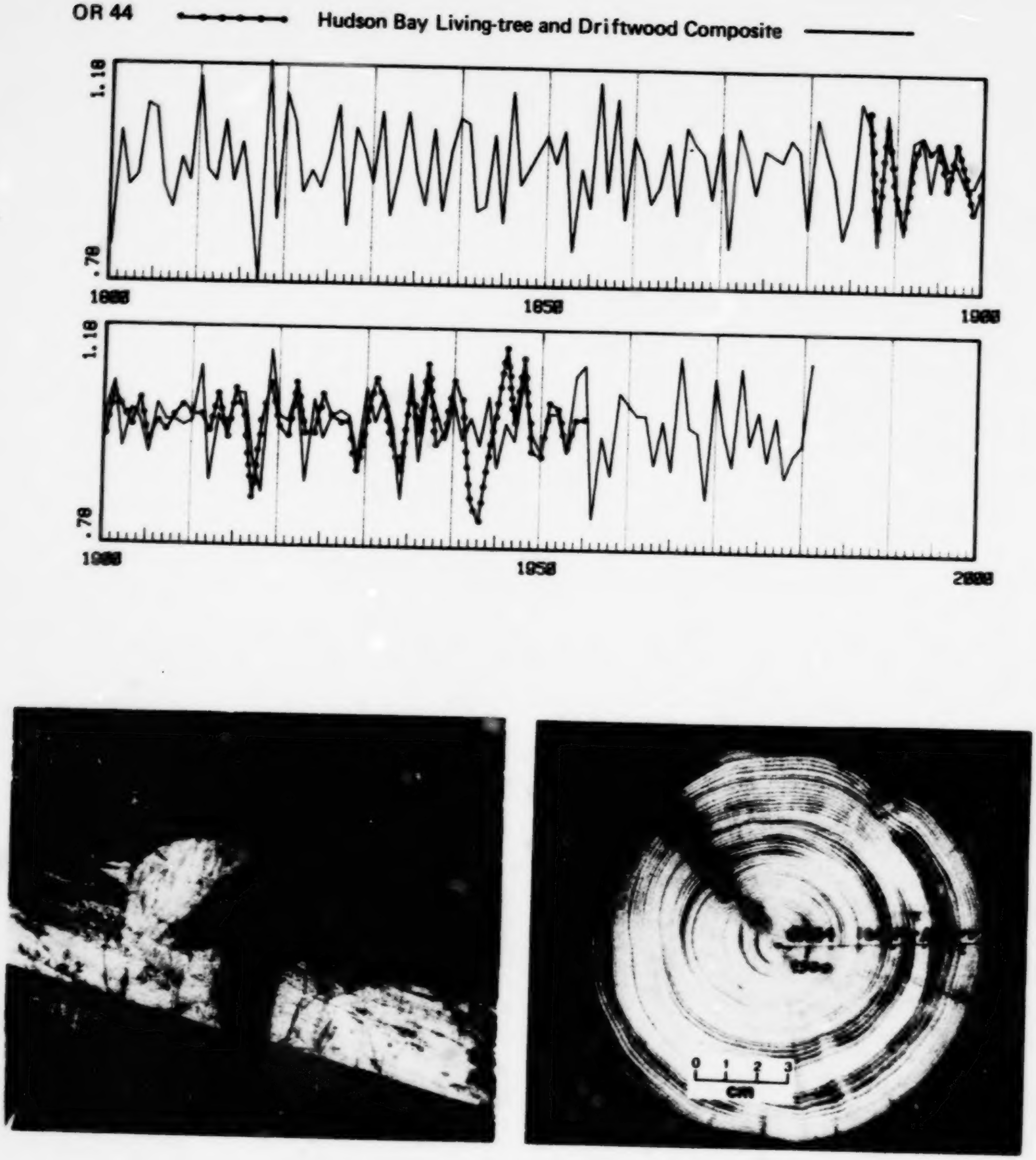
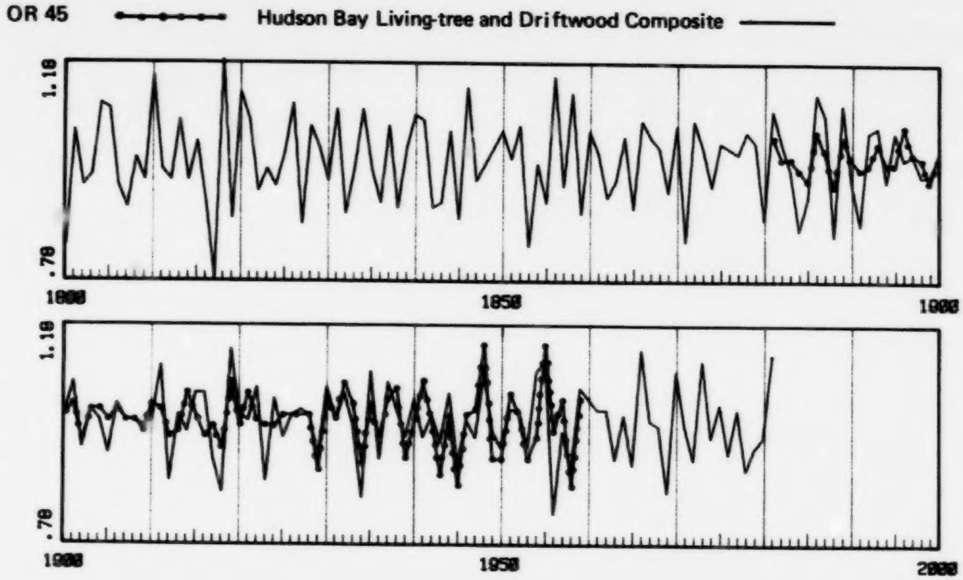


FIGURE 5J: *Dated Owl River driftwood sample (OR 44).*



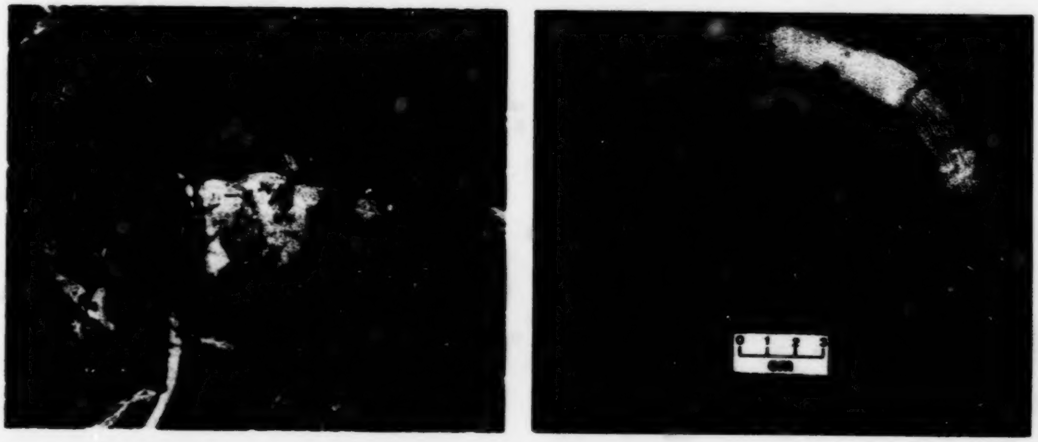
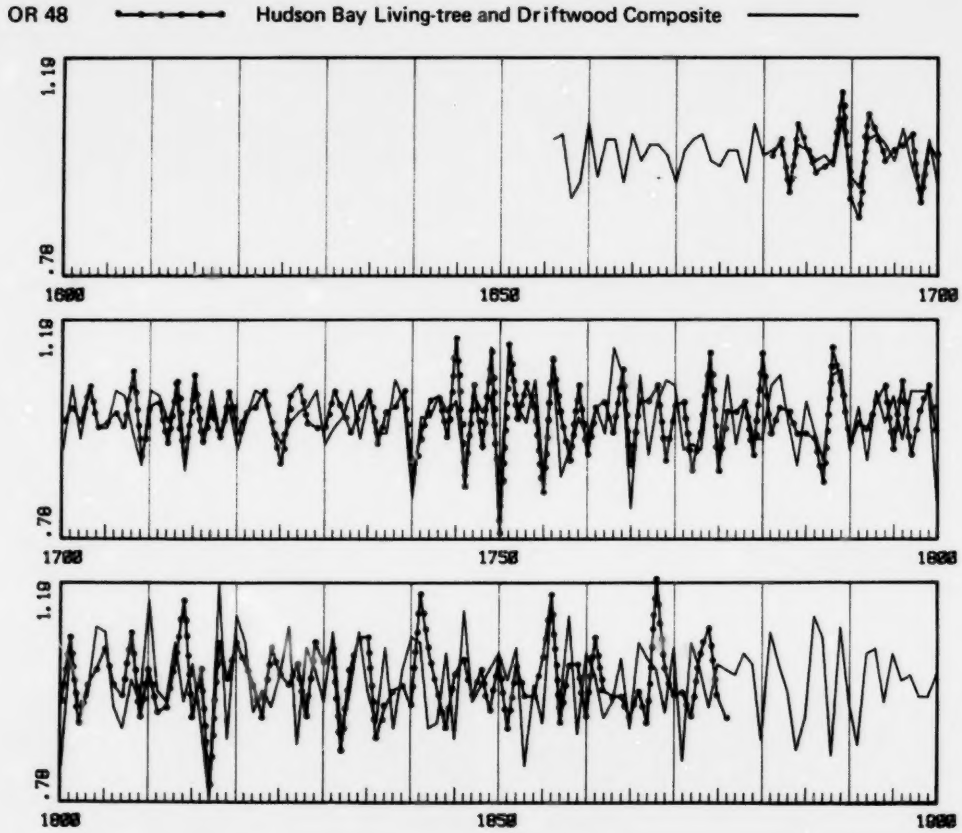


FIGURE 5K: *Dated Owl River driftwood sample (OR 45).*



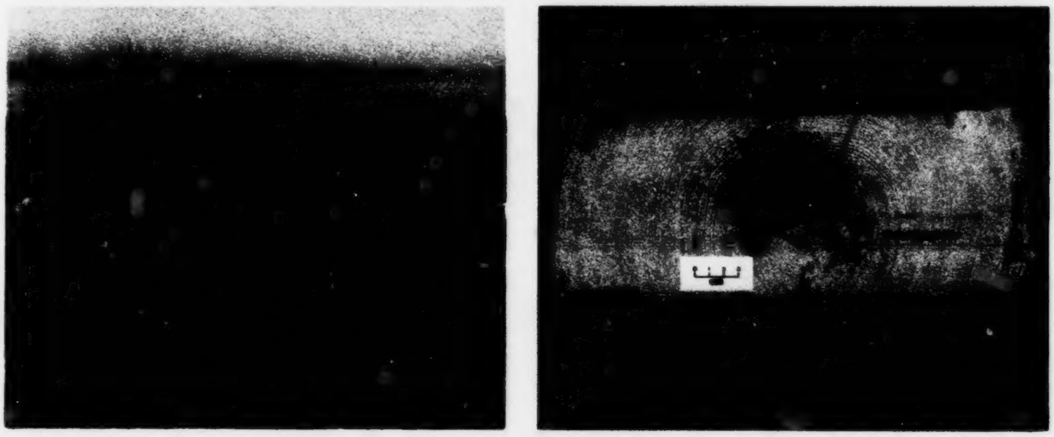


FIGURE 5L: *Dated Owl River driftwood sample (OR 48).*

Deriving the Chronologies

The "raw data" consist of: (1) ring-width values in 0.01 mm units, (2) maximum ring-density values in g/cm^3 measured at 0.01 mm increments along the scanned portion of a tree-ring sample. These raw data are "standardized" by converting them to indices (ratio of observed value to fitted trend, yielding values with a mean of 1.00) by removing the growth trend (and sometimes other trends or fluctuations). The standardized data (indices) for all samples are then "summarized", or averaged, to produce a summary or "master" chronology for the site.

This procedure is illustrated in Figure 6. In a previous publication (Parker *et al.* 1981) the "A", "B" and "C" components have been described: "A" defined as the growth trend; "B", the short-term fluctuations greater than 10 years in length; and "C", the year-to-year variations. Various data processing programs are used to produce "A", "B", "C" and "B & C" chronologies from the raw data of each increment core. These data are then averaged with data from other tree-ring sample series to produce the summary chronologies.

If increment core data are averaged without removing the growth trend, non-climatic fluctuations related to the age of the tree will be included in the chronology. Therefore, the growth trend must be removed. However, variation due to climate may be removed inadvertently, if proper techniques are not used in this procedure.

A method for removing the growth trend (the "A" component) from tree-ring series that was applied to data processed in this study, used a digital-filter with a length of 60 years (Parker 1970B). This method is designed to remove the growth trend and non-climatic surges in growth, such as tree growth release after a forest fire. Tree-ring indices (in the form of the "B & C" chronology) are produced by calculating deviations from a growth-trend line through the raw data values.

The "B" and "C" chronologies are obtained from the tree-ring indices (the "B & C" chronology). This is done by using a digital-filter technique with a length of 13 years (Parker 1970B). The "B" chronology is the estimated curve which is a weighted running mean. Deviations from this line are the year-to-year fluctuations, or the "C" chronology. The "C" chronology type has proven to be the form most useful for dating purposes, and is the type of chronology used here.

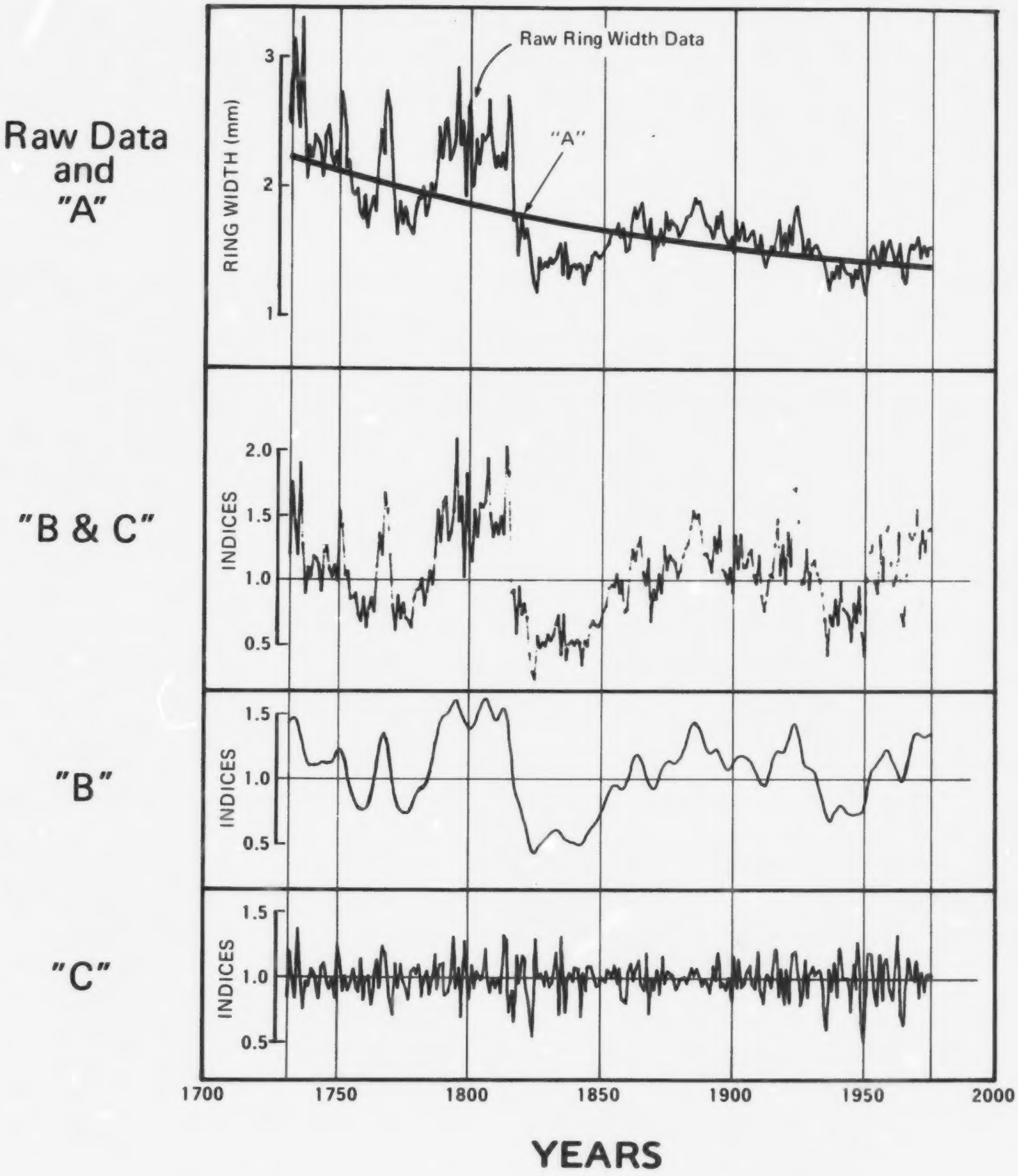


FIGURE 6: *The "A", "B", and "C" components of a tree-ring series. Data used in this example are ring-width values of a white spruce tree from Cri Lake, Québec.*

Computer Crossdating

All tree-ring dates for the driftwood samples in this study were obtained by using a statistical technique. This was accomplished by means of a computer program known as the Shifting Unit Dating Program (SUDP), which employs cross-correlation analysis (Parker 1967, 1970B). The program correlates a specified portion, or unit, of the undated tree-ring series with the dated master series in all possible positions. If the former are designated as X rings and the latter Y rings, the possible number of matches for the undated unit is Y - X + 1. The positions and correlation coefficients of the the three best matches of this undated unit with the master chronology are recorded. The computer then compares a new unit of the undated series with the master in the same manner. This new unit is shifted one ring in time from the initial unit. Again, the positions and correlation coefficients of the three best matches are recorded. This procedure is repeated with additional units until all possible units of the undated chronology have been matched with the master. If Z is the total number of rings in the undated series, the number of such comparisons is Z - X + 1. A date is obtained if a large number of the most highly correlated matches are the same. Additional confidence is provided if both density and width variables yield the same date. Results were checked by visually comparing graphical plots of master and driftwood ring series.

Wood Sample Examination

For most of the driftwood samples, the number of annual rings processed on the x-ray densitometry system did not represent the full number of rings contained in the sample, because of deterioration at sample surfaces. However, tree-ring dates given represent rings present on the whole wood sample rather than just those rings measured.

This was done by examining the wood under a low-power binocular microscope after it had been prepared by surfacing it with a surgical scalpel or by sanding it with a belt sander using a series of progressively finer grit sizes of sandpaper. Although the poorly preserved rings near the sample surfaces could not be measured by x-ray densitometry, this procedure allowed a ring count to be made, and the inside and outside dates of the ring series could be recorded.

Climatic Comparisons

Parker's (1976) technique for comparing relationships between weather factors and tree-ring widths, and between weather factors and density, by preparing bar graphs of correlation coefficients, was used.

Data from individual trees from the Churchill River black spruce site, were averaged to produce composite ring width and maximum ring density "C" type chronologies. These series were correlated with total monthly precipitation and mean monthly temperature records from Churchill for the six months from April to September, for the period from 1943 to 1980.

RESULTS AND DISCUSSION

Tree-Ring Dates of Driftwood from Owl River and Churchill River

The ring width and maximum ring density chronologies derived from black spruce samples from the Churchill River site provided information for dating the Churchill and Owl River driftwood samples, as well as being useful for determining the relationship between climate and tree growth for that area. These chronologies are presented in tabular and plotted form in Appendix 1.

Four tree-ring samples were dated on the first attempt by using the Shifting Unit Dating Program to compare Owl River driftwood with Churchill River living-tree ring width and maximum ring density chronologies. Maximum ring density proved to be the better of the two parameters for crossdating purposes, and in all further analyses this variable was used.

The dated driftwood samples were incorporated into a composite ("master") chronology, consisting of the dated driftwood series and the living-tree chronology. This composite was run against the driftwood samples again.

More samples were dated by this technique, including one of the four samples collected in 1979 from the beach at Churchill (Figure 3).

Some of the tree-ring series from the driftwood appeared to be of good enough quality to date but were apparently too old to match the relatively short Churchill River chronology. An existing white spruce (*Picea glauca* (Moench) Voss) chronology (Parker *et al.* 1981) from the Great Whale River area (Figure 7), that extends back to 1700, was run

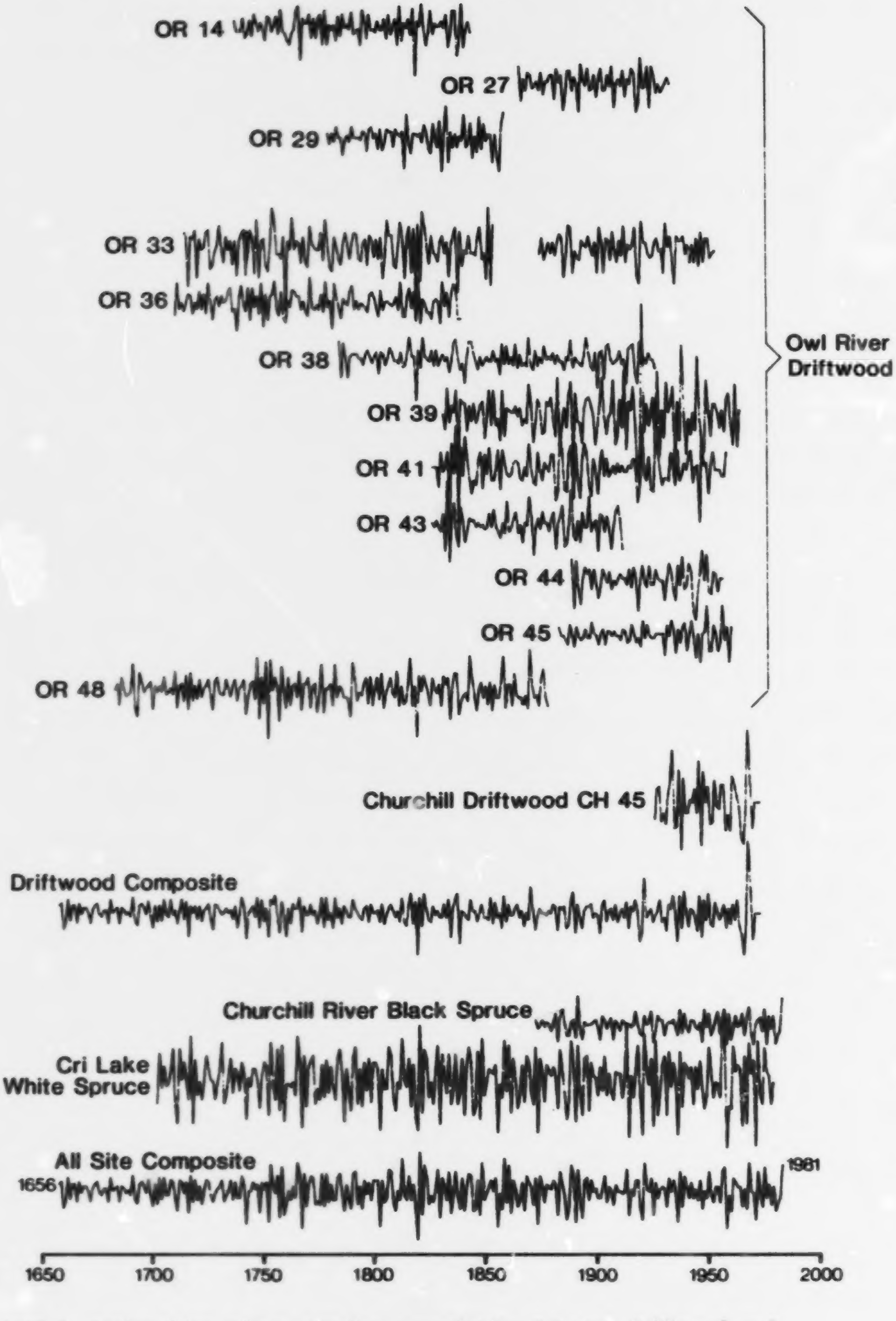


FIGURE 7: *Broken-line plots showing crossdating between driftwood and composite chronologies. The "C" type of maximum ring density is used.*

against the corresponding Churchill River chronology. It matched in the correct place with respect to calendar year. (The correct calendar year dates for these chronologies were known, because they were derived from living-tree samples of which the collection dates were known.) The computer crossdating program was used to run the driftwood against the Great Whale River chronology and more samples were dated. These were incorporated into a new composite master, and this master was run against the driftwood again. This procedure was continued until 12 Owl River driftwood samples were dated. Final results for the 30 driftwood samples processed from Owl River are: 12 dated, 13 not dated, and 5 not expected to date because they are Douglas-fir, western red cedar and red pine that were apparently introduced into the area as timbers by man from other locations.

One of the four samples from the Churchill beach was dated. The driftwood chronology, for both Churchill and Owl River, extends from 1656 to 1972. This represents the innermost to the outermost ring measured on the x-ray densitometry system. (Some annual rings, that were formed either before or after this time, were not measured because of their poor state of preservation.) This chronology, derived from dead wood, is longer than any living-tree density chronology developed for the area.[1] Broken-line plots illustrating these chronologies, and the crossdating with the master chronologies, are presented in Figure 7 and in Appendices 1 and 2. Tree-ring dates and other data related to the driftwood samples are given in Table 1.

Crossdating Quality of Trees from the Hudson Bay Area

Although the best-quality dendrochronological material in Canada comes from short-summer areas such as the Mackenzie Delta or the dry river valleys in Western Canada, the Hudson Bay area produces tree-ring material adequate for research purposes.

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[1] Ed. note: Three months after this manuscript was received, Jacoby and Ulan (1982) published a paper on reconstruction of past ice conditions in the Churchill River estuary using tree rings. This study was based on 39 cores from 15 trees taken from a sampling area immediately south of Churchill airport. Ten of the 15 cores extend back to 1686, or earlier.

TABLE 1: *DATED DRIFTWOOD FROM CHURCHILL AND OWL RIVER.*[1]

FIELD NUMBER	BEACH	SPECIES	INSIDE ON WOOD	INSIDE MEASURED	OUTSIDE MEASURED	OUTSIDE ON WOOD
OR-14	1E	S	1732	1736	1842	1849vv
OR-27	0	S	1856P	1864	1932	1934vv
OR-29	0	S	1697P	1777	1857	1858vv
OR-33	0	EL	1703P	1712	1952	1958vv
OR-36	0	S	1698P	1708	1837	1944vv
OR-38	0	S	1772P	1782	1925	1926vv
OR-39	0	S	1827P	1829	1963	1967vv
OR-41	0	S	1814P	1824	1957	1961v
OR-43	0	S	1815P	1824	1910	1913vv
OR-44	0	S	1883P	1887	1955	1960vv
OR-45	0	EL	1873P	1881	1959	1960vv
OR-48	0	S	1676P	1681	1876	1890vv
CH-45	-	S	1932P	1924	1971	1972 r

[1] Key: OR = Owl River, CH = Churchill, S = black spruce or white spruce, EL = tamarack, P = pith, r = outside ring present, vv = very variable outside and v = variable outside.

This is demonstrated in three ways:

(1) Crossdating can be obtained between living-tree site chronologies over long distances. The Churchill River black spruce matched correctly with Cri Lake white spruce from near Great Whale River, Québec - a distance of 965 km away. In another study conducted recently by Forintek for the Canadian Forestry Service (Jozsa *et al.* 1982), tree-ring chronologies from Manitoba, Alberta and the Northwest Territories were compared with the Churchill River chronologies. In many cases, crossdating was adequate (using maximum ring density) for samples separated by considerable distances. For example, an r value of 0.597 (for the period 1870-1978) was obtained between Churchill River black spruce and Suwannee River white spruce, separated by a distance of about 400 km; and a correlation between maximum ring density chronologies of trees from Churchill River, and from Prelude Lake, near Yellowknife, Northwest Territories (about 1,200 km apart) produced an r value of 0.369.

(2) Dates were obtained for a high percentage of the samples of Owl River driftwood. Driftwood is far from being the ideal material for analytical purposes, due to the extent of deterioration. In spite of this, almost all processed samples from the youngest beach at Owl River could be dated; and they crossdated with trees as far away as Great Whale River.

(3) Crossdating was obtained for three species: black spruce, white spruce and tamarack. The response of these species to climate is similar enough to produce chronologies that crossdate well with one another. This provides more material for dating purposes and more varied data for climatic studies.

Climatic Relationships

In the comparison of all possible combinations of ring width and maximum ring density correlated with temperature and precipitation for the six months from April to September (Figure 8), significant correlations were obtained only between temperature and maximum ring density. As for other areas in northern Canada, as demonstrated by tree-ring studies in the Mackenzie Delta (Parker 1976) and in northern Québec (Parker *et al.* 1981), the highest correlation was obtained between August temperature and maximum ring density ($r = 0.57$, $n = 19$).

The dotted lines in Figure 8 are arbitrarily placed at 0.5 and -0.5 for points of reference only and do not represent significance levels. Accurate significance levels are difficult to determine for time series of this type, because adjacent values in the series are not independent of one another. Note that the highest correlations are produced when maximum ring density and temperature are compared. A positive correlation is obtained from all months from April to September, the highest being for the month of August.

Preliminary investigation was undertaken to attempt to improve correlations between tree-ring data and weather records by combining weather data for a number of months into some form of weighted index series. Initial findings supported the validity of the approach, and indicated that tree-ring width and density chronologies, as developed here, are useful for this purpose.

CONCLUSIONS

Almost all processed samples obtained from the youngest beaches could be dated, whereas none of the samples from the oldest beaches was dated. This demonstrates that: (1) it is possible to obtain tree-ring dates from driftwood in the area; (2) if and when older tree-ring chronologies are built, it should be possible to date wood from older beaches; (3) wood

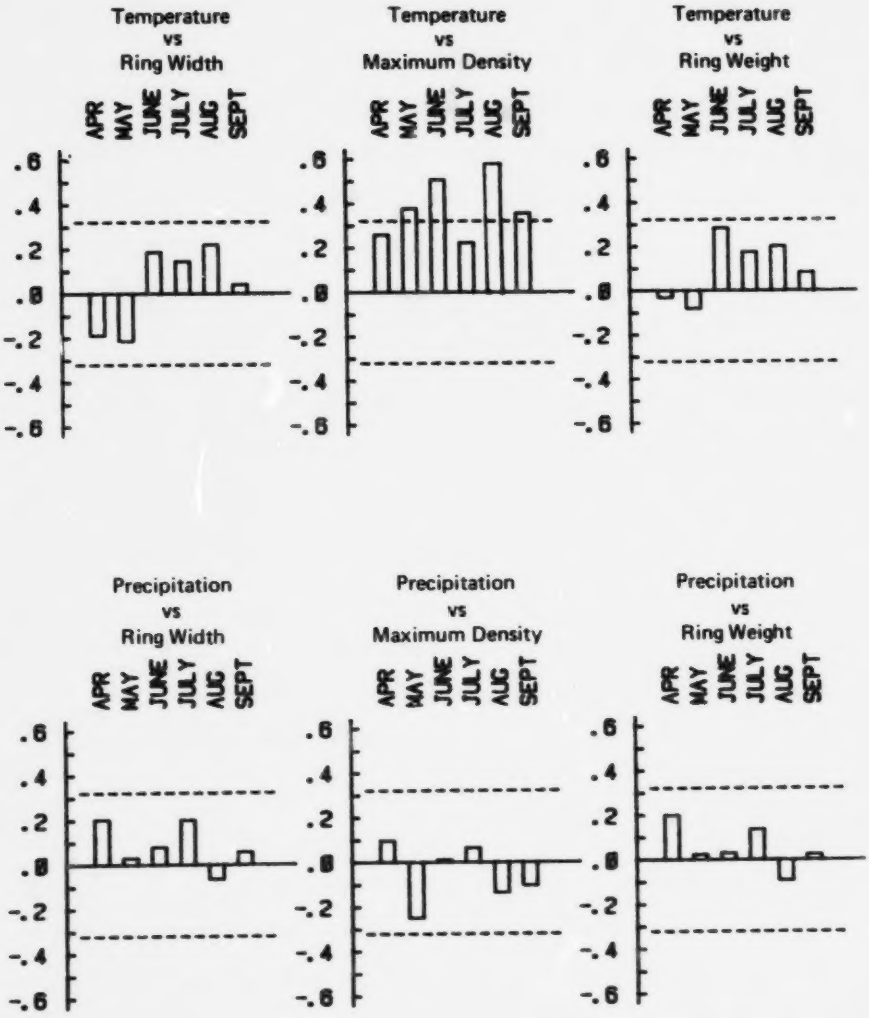

FIGURE 8: *Bar graphs of correlation coefficients calculated in comparisons of Churchill River tree-ring chronologies and weather data from Churchill, Manitoba.*

from these old beaches can be used to build longer chronologies. Further, dating of driftwood from the Hudson Bay area will permit various applications of dendrochronology.

Our results show that tree-ring dates can be obtained from Hudson Bay material. They provide, in the form of tree-ring width and density chronologies, a data base for more tree-ring dating and for climatic studies. They also demonstrate that, in order to build long tree-ring chronologies, dead-wood samples, such as driftwood, must be studied.

RECOMMENDATIONS

The following studies should be initiated to extend tree-ring chronologies and the relationship between climate and tree growth in Hudson Bay and Canadian Arctic Islands regions:

(1) Relationships between tree-ring width and density variables, and weather data should be examined in detail. Equations need to be derived that will convert tree-ring data directly into proxy weather records.

(2) The large timbers used in the construction of York Factory should be sampled to provide material for building long tree-ring chronologies for that area.

(3) A project to collect and date driftwood from areas along the Hudson Bay shoreline and from the Canadian Arctic Islands is needed. Possibly tree-ring chronologies that are several thousand years long can be developed.

(4) A project should be undertaken to collect and process samples from living tamarack trees from the Churchill area. Some driftwood of this species was dated and width and density chronologies for tamarack would be useful for dating purposes and climatic studies.

SUMMARY

Tree-ring dates were obtained from driftwood samples from the present beach at Churchill, Manitoba and from raised beaches at the mouth of Owl River that flows into Hudson Bay midway between Churchill and York Factory. The technique of x-ray densitometry was used to build tree-ring width and density chronologies for the driftwood samples and for living black spruce trees from a site on Churchill River 65 km from Churchill. Computer crossdating was used to date the driftwood, and some samples were dated against white spruce chronologies derived from trees from Great Whale River, 965 km from the Churchill River site. The living-tree chronology for the Churchill area goes back only to 1870, but Owl River driftwood has extended the chronology back to 1656. Tree-ring parameters were compared with weather data from Churchill. Maximum ring density correlates better with climatic factors than does ring width, and temperature relates better to tree rings than does precipitation.

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APPENDIX 1: *COMPOSITE TREE-RING CHRONOLOGIES IN TABULAR AND PLOTTED FORM. RING WIDTH AND MAXIMUM RING DENSITY ARE PRESENTED IN THE "C" TYPE OF CHRONOLOGY. ONLY MAXIMUM RING DENSITY IS PLOTTED.*

CHURCHILL RIVER BLACK SPRUCE MAXIMUM DENSITY "C" CHRONOLOGY
YEARS: 1870 1981

	TREE RING INDICES										NUMBER OF RADII									
DATE	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1870	1.02	.98	1.00	1.02	.99	1.01	1.00	.97	1.01	1.05	1	1	1	1	1	1	1	1	1	1
1880	.92	1.04	1.07	1.01	.95	.95	1.01	1.02	.94	1.13	1	1	1	1	1	1	1	1	1	1
1890	.98	.93	1.01	1.00	1.00	1.00	1.01	1.02	.99	.93	1	3	3	7	9	11	12	12	12	12
1900	1.04	1.02	.98	1.01	1.03	.93	1.02	1.00	.97	1.02	14	15	17	17	17	17	17	17	19	19
1910	1.01	.99	1.00	.99	1.00	1.06	1.00	.96	.95	1.04	20	20	20	20	20	22	22	22	22	22
1920	1.00	1.01	1.06	.92	.97	1.04	1.02	1.02	.95	1.00	22	22	22	22	22	22	22	22	22	22
1930	1.01	1.01	1.02	.99	.95	1.07	.96	1.05	.99	.96	22	22	22	22	22	22	22	22	22	22
1940	1.02	1.02	.99	.98	1.01	.92	1.07	.99	1.05	.95	22	22	22	22	22	22	22	22	22	22
1950	.98	1.02	1.06	.96	1.01	1.07	.91	1.05	.93	.98	22	21	21	21	21	21	21	21	21	21
1960	1.04	.99	1.00	1.05	.95	1.02	1.08	.97	.91	1.00	21	21	21	21	21	21	21	20	20	20
1970	1.02	1.03	.97	1.07	.91	1.04	.98	1.04	.91	.95	20	20	20	20	20	20	20	20	20	20
1980	.97	1.12									20	19								

CHURCHILL RIVER BLACK SPRUCE RING WIDTH "C" CHRONOLOGY
YEARS: 1870 1981

	TREE RING INDICES										NUMBER OF RADII									
DATE	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1870	1.03	1.08	.91	.96	1.10	1.10	.84	1.02	1.30	.73	1	1	1	1	1	1	1	1	1	1
1880	.52	.63	1.01	1.23	1.09	1.00	1.05	1.11	1.01	.96	1	1	1	1	1	1	1	1	1	1
1890	.96	1.06	.89	1.06	.96	.99	.96	1.01	.92	.92	1	3	3	7	9	11	12	12	12	12
1900	1.16	.87	1.07	.96	.93	1.02	1.02	1.07	.97	1.02	14	15	17	17	17	17	17	17	19	19
1910	.97	.98	.96	1.05	1.08	.92	1.02	1.04	1.00	.95	20	20	20	20	20	22	22	22	22	22
1920	.89	1.14	1.03	.91	.98	1.07	1.02	.95	.90	1.11	22	22	22	22	22	22	22	22	22	22
1930	.92	.98	1.00	.94	1.10	1.21	.89	.82	.93	1.00	22	22	22	22	22	22	22	22	22	22
1940	1.02	.93	.97	1.05	.92	.95	1.19	1.01	1.05	.94	22	22	22	22	22	22	22	22	22	22
1950	.87	1.12	.80	1.14	1.06	1.13	.68	1.11	.81	1.14	22	21	21	21	21	21	21	21	21	21
1960	1.01	1.04	.96	1.11	.74	1.04	1.19	.99	.89	1.12	21	21	21	21	21	21	21	20	20	20
1970	.93	.93	1.11	.92	.98	.99	.95	.97	1.11	1.08	20	20	20	20	20	20	20	20	20	20
1980	.68	1.19									20	19								

APPENDIX 1: (Cont'd)

CRI LAKE WHITE SPRUCE RING WIDTH "C" CHRONOLOGY
YEARS: 1700 1977

	TREE RING INDICES										NUMBER OF RADII									
DATE	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1700	.94	.99	1.09	1.00	1.01	.93	1.00	1.03	.93	1.14	2	2	2	2	2	2	2	2	2	2
1710	.74	1.04	1.23	1.08	.88	1.16	.83	.94	.85	1.02	2	2	2	2	2	2	2	2	2	2
1720	1.14	1.10	.78	.98	.95	1.08	.96	1.14	1.09	1.05	4	4	4	4	4	4	4	4	4	4
1730	.90	.93	.92	1.16	1.10	.76	1.10	1.00	.86	1.07	5	5	6	6	6	6	6	6	6	6
1740	.96	1.00	1.00	1.07	.91	1.05	1.07	1.01	.86	.96	6	6	6	6	6	6	6	6	6	6
1750	.92	1.24	1.11	.85	.96	.89	.92	1.17	1.05	.95	7	7	7	7	7	7	7	7	7	7
1760	1.02	.83	.95	1.28	.78	.94	1.04	.85	1.16	1.15	9	9	9	9	9	9	9	9	9	9
1770	1.02	.96	.88	1.01	.91	1.04	.95	1.01	.87	1.02	11	11	11	11	11	11	11	11	11	11
1780	1.06	1.06	1.19	.85	.86	.98	.84	1.04	1.13	1.03	12	12	12	12	12	12	12	12	12	12
1790	1.03	1.03	.94	.94	.97	1.21	.87	1.15	.78	1.28	14	14	14	14	14	14	14	14	14	14
1800	.82	.87	1.00	.96	1.06	1.05	1.03	1.12	.96	.95	15	15	15	15	15	15	15	15	15	15
1810	.94	.96	1.00	.93	1.28	1.24	.71	.82	.73	1.12	15	15	15	15	15	15	15	15	15	15
1820	1.06	1.10	1.10	.96	.73	.79	1.23	.88	.98	1.01	15	15	15	15	15	15	15	15	15	15
1830	1.08	.83	1.08	1.11	1.10	.85	1.04	.91	.97	1.12	15	15	15	15	15	15	15	15	15	15
1840	.99	1.14	1.07	.68	.91	.98	1.10	1.01	.89	1.05	15	15	15	15	15	15	15	15	15	15
1850	.99	1.02	.97	1.03	1.08	.96	1.13	.91	1.05	.91	16	16	16	16	16	16	16	16	16	16
1860	.88	.99	.94	1.15	1.07	1.06	.85	1.00	1.18	.80	16	16	16	16	16	16	16	16	16	16
1870	1.04	.87	.99	.92	1.15	.93	1.08	1.03	.99	.88	16	16	16	16	16	16	16	16	16	16
1880	1.02	1.01	1.08	.94	.95	1.00	.99	1.13	1.04	.89	16	16	16	16	16	16	16	16	16	16
1890	.99	.99	.94	1.03	.99	1.15	.99	.97	.93	.93	16	16	16	16	16	16	16	16	16	16
1900	.96	1.10	.92	1.02	1.01	.98	1.03	1.06	1.02	.94	17	17	17	17	16	16	16	16	16	16
1910	1.06	1.08	.80	1.02	1.03	.88	.97	1.17	.95	1.09	17	17	17	17	17	17	17	17	17	17
1920	.80	1.02	.88	1.23	1.14	.98	.82	.92	1.17	.78	17	17	17	17	17	17	17	17	17	17
1930	1.13	1.06	1.04	1.00	.92	1.02	.86	1.05	.95	1.00	17	17	17	17	17	17	17	17	17	17
1940	.90	1.11	1.07	.97	1.05	.86	.97	1.08	1.28	.85	17	17	17	17	17	17	17	17	17	17
1950	.69	1.09	1.00	.98	1.05	.95	.97	1.03	1.02	1.11	16	16	16	16	16	16	16	16	16	16
1960	1.01	.92	.97	1.23	.88	.72	1.10	1.07	1.00	1.00	16	16	16	16	16	16	16	16	16	16
1970	1.02	.91	1.08	.99	1.12	.97	1.01	.89			16	16	16	16	16	16	15	15		

APPENDIX 1: (Cont'd)

CRI LAKE WHITE SPRUCE MAXIMUM DENSITY "C" CHRONOLOGY
YEARS: 1700 1977

	TREE RING INDICES										NUMBER OF RADII									
DATE	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1700	.88	1.12	.96	1.06	.97	.98	1.04	1.14	.89	.80	2	2	2	2	2	2	2	2	2	2
1710	1.13	1.00	1.07	1.00	.92	1.20	.79	1.09	.93	.99	2	2	2	2	2	2	2	2	2	2
1720	.92	.99	1.11	1.04	1.00	1.00	.92	.98	1.03	1.16	4	4	4	4	4	4	4	4	4	4
1730	.89	.94	1.01	1.10	.94	1.05	1.03	.95	1.08	1.03	5	5	6	6	6	6	6	6	6	6
1740	.82	1.01	.98	1.05	1.05	1.00	.88	1.03	1.08	1.06	6	6	6	6	6	6	6	6	6	6
1750	.83	1.17	1.00	.90	1.16	.86	1.16	.80	.98	.98	7	7	7	7	7	7	7	7	7	7
1760	.96	1.00	.93	1.21	1.08	.77	1.11	.88	1.06	1.09	9	9	9	9	9	9	9	9	9	9
1770	1.11	.89	.95	.90	1.08	.93	1.09	.93	1.06	.98	11	11	11	11	11	11	11	11	11	11
1780	.90	1.11	1.13	1.03	.81	1.05	.96	.87	1.10	1.14	12	12	12	12	12	12	12	12	12	12
1790	.89	1.05	.88	1.07	.96	1.09	.90	1.08	1.08	1.07	14	14	14	14	14	14	14	14	14	14
1800	.77	1.05	.96	.95	1.15	1.11	.92	.86	1.00	.96	15	15	15	15	15	15	15	15	15	15
1810	1.20	.99	.97	1.10	.88	1.08	.83	.76	1.25	.85	15	15	15	15	15	15	15	15	15	15
1820	1.14	1.10	.92	.99	.88	1.03	1.17	.79	1.12	1.01	15	15	15	15	15	15	15	15	15	15
1830	.95	1.11	.90	.95	1.13	.89	.95	1.10	.84	1.06	15	15	15	15	15	15	15	15	15	15
1840	1.16	1.08	.84	.87	1.12	.82	1.19	.94	.99	1.06	15	15	15	15	15	15	15	15	15	15
1850	1.04	1.03	1.07	.76	.99	.92	1.19	.95	1.16	.85	16	16	16	16	16	16	16	16	16	16
1860	1.09	1.00	.87	.95	1.07	.90	1.11	1.08	.96	.89	16	16	16	16	16	16	16	16	16	16
1870	1.16	.76	1.10	1.04	.90	1.07	1.04	1.02	1.05	1.02	16	16	16	16	16	16	16	16	16	16
1880	.87	1.15	1.04	.94	.81	.91	1.18	1.08	.81	1.16	16	16	16	16	16	16	16	16	16	16
1890	.94	.84	1.10	1.11	.85	1.09	1.02	1.01	.93	1.06	16	16	16	16	16	16	16	16	16	16
1900	.96	1.11	.93	1.02	.95	.90	1.04	1.03	1.03	.92	17	17	17	17	16	16	16	16	16	16
1910	1.00	1.26	.73	1.02	.92	1.03	1.16	.93	.75	1.21	17	17	17	17	17	17	17	17	17	17
1920	1.04	.99	1.10	.78	1.18	.84	.95	1.06	1.11	.84	17	17	17	17	17	17	17	17	17	17
1930	1.14	.97	1.08	1.00	.75	1.13	.88	1.08	1.06	1.01	17	17	17	17	17	17	17	17	17	17
1940	1.06	.89	1.07	.96	1.09	.96	.87	.94	1.15	1.04	17	17	17	17	17	17	17	17	17	17
1950	.92	1.00	.98	.91	1.25	1.21	.68	.87	.87	1.17	16	16	16	16	16	16	16	16	16	16
1960	1.05	1.07	1.06	.78	1.11	.79	1.18	1.03	1.09	.69	16	16	16	16	16	16	16	16	16	16
1970	1.18	.93	.89	1.16	1.04	1.02	.88	.99			16	16	16	16	16	16	15	15		

APPENDIX 1: (Cont'd)

HUDSON BAY DRIFTWOOD RING WIDTH "C" CHRONOLOGY
YEARS: 1656 1971

	TREE RING INDICES										NUMBER OF RADII									
DATE	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1650							.91	1.11	.97	1.01							1	1	1	1
1660	1.05	.96	.98	1.07	1.08	.98	.86	1.10	.91	.79	1	1	1	1	2	2	2	2	2	2
1670	1.22	1.08	.98	.89	1.03	.98	1.07	1.06	.94	.91	2	2	2	2	2	2	2	2	2	2
1680	1.05	.98	1.04	.93	.95	1.12	1.05	.96	.92	1.04	2	4	4	4	4	4	4	4	4	4
1690	1.06	.96	1.02	1.00	.94	1.08	1.09	.89	.89	1.07	4	4	4	4	4	4	4	4	4	4
1700	1.00	.97	1.06	1.00	.91	.95	1.01	1.05	.96	.96	4	4	4	4	4	4	4	4	5	5
1710	1.06	1.06	.98	.92	.87	1.00	1.04	1.21	.80	1.07	5	5	6	6	6	6	6	6	6	6
1720	.89	1.05	.99	1.05	.90	1.00	1.04	1.04	.97	1.02	6	6	6	6	6	6	6	6	7	7
1730	1.04	.99	.94	1.03	.90	.99	1.06	.91	1.02	.99	7	6	6	6	6	7	7	7	7	7
1740	.95	1.06	1.13	.93	.96	1.01	.91	1.01	.99	1.07	7	7	7	7	7	7	7	7	7	7
1750	.88	.99	1.04	1.01	1.05	.96	1.06	1.06	.66	.91	7	7	7	7	7	7	7	6	6	6
1760	.93	.95	1.17	1.12	.97	.91	1.03	.89	.97	.99	6	6	6	6	7	7	7	7	7	7
1770	1.03	1.05	1.07	.99	1.00	1.02	1.02	.87	1.00	.91	7	7	7	7	7	7	7	7	7	7
1780	1.07	.93	1.01	.83	1.24	.95	.83	.95	1.08	1.05	7	7	8	9	10	10	10	10	10	10
1790	1.07	1.02	.94	1.02	1.02	.91	1.02	1.02	1.04	1.01	10	10	10	10	10	10	10	10	10	10
1800	.81	1.06	.96	1.05	.93	1.13	.91	1.06	1.01	.90	10	10	10	10	10	10	10	10	10	10
1810	1.17	.93	.95	.94	1.05	1.05	.96	1.02	.99	.92	10	10	10	10	10	10	10	10	10	10
1820	1.01	1.00	1.08	1.01	.95	.82	1.09	.93	1.05	.97	10	10	10	10	12	12	12	12	12	12
1830	.94	1.02	1.00	.98	1.12	1.00	1.04	.80	1.09	.90	12	12	13	12	12	12	11	12	11	11
1840	1.00	.94	1.06	.99	.98	1.03	1.00	.88	.93	1.06	11	11	11	10	11	11	11	10	10	10
1850	1.16	.88	1.03	.94	1.06	1.00	.97	.92	1.02	1.03	10	10	10	9	9	9	9	9	9	9
1860	.96	1.04	1.01	.95	1.11	.93	1.05	.98	1.09	.84	9	9	9	9	10	10	10	10	10	10
1870	1.06	1.02	.95	1.08	.91	1.08	.83	1.06	1.12	.95	10	10	10	12	12	12	12	11	11	11
1880	.93	.91	1.04	1.10	.99	.96	1.01	1.12	.95	.93	12	13	13	14	14	14	14	15	15	16
1890	.94	.97	1.04	1.04	1.00	1.11	.90	.92	1.00	.97	16	16	16	16	16	16	16	16	16	16
1900	1.07	.94	.94	1.10	.98	.98	.98	.89	1.04	1.07	16	16	16	16	16	16	16	15	15	15
1910	.96	1.03	.94	1.05	.99	.97	.90	1.06	1.03	1.10	15	14	14	14	14	14	14	14	14	14
1920	.92	1.04	.93	1.05	.97	1.02	.95	.98	1.02	.93	14	14	14	14	16	15	14	14	14	14
1930	1.00	.94	1.10	.95	.93	1.14	.95	1.01	1.01	1.01	14	14	14	12	12	12	12	12	12	12
1940	1.08	1.07	.84	.77	1.02	.84	1.14	.96	1.11	.88	12	12	12	12	12	12	12	12	12	12
1950	1.04	1.10	.88	1.01	1.03	1.01	.92	1.04	.89	1.16	12	11	11	10	10	10	7	7	5	6
1960	1.02	.96	1.02	.89	.81	.96	1.33	1.12	.88	1.00	4	3	3	3	1	1	1	1	1	1
1970	1.00	1.00									1	1								

APPENDIX 1: (Cont'd)

HUDSON BAY DRIFTWOOD MAXIMUM DENSITY "C" CHRONOLOGY
YEARS: 1656 1971

	TREE RING INDICES										NUMBER OF RADII									
DATE	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1650							1.03	1.04	.92	.95							1	1	1	1
1660	1.06	.96	1.03	1.03	.95	1.04	.99	1.02	1.02	1.00	1	1	1	1	2	2	2	2	2	2
1670	.95	1.01	1.03	1.04	.99	.98	1.01	1.01	.95	1.06	2	2	2	2	2	2	2	2	2	2
1680	1.00	1.01	1.02	.95	1.02	1.01	.99	1.00	.98	1.07	2	4	4	4	4	4	4	4	4	4
1690	.96	.94	1.03	1.04	1.02	.99	1.05	.90	.93	1.03	4	4	4	4	4	4	4	4	4	4
1700	.96	1.03	.96	1.06	.99	.98	1.06	.99	1.01	.95	4	4	4	4	4	4	4	4	5	5
1710	1.01	1.06	.97	1.05	.89	1.03	1.00	1.03	.97	1.03	5	5	6	6	6	6	6	6	6	6
1720	.96	1.01	1.32	1.04	.97	.92	1.04	1.03	1.01	.99	6	6	6	6	6	6	6	6	7	7
1730	1.00	1.02	1.00	1.01	.97	1.03	.93	.99	1.07	1.03	7	6	6	6	6	7	7	7	7	7
1740	.88	1.00	1.01	1.03	.98	1.07	.93	1.06	.96	1.02	7	7	7	7	7	7	7	7	7	7
1750	.89	1.06	1.04	1.08	.99	.91	1.05	.90	.89	1.02	7	7	7	7	7	7	7	6	6	6
1760	.95	1.04	1.02	1.02	1.07	.91	1.03	.99	.99	1.04	6	6	6	6	7	7	7	7	7	7
1770	.99	1.01	.95	.99	1.07	.93	1.07	.97	1.00	.93	7	7	7	7	7	7	7	7	7	7
1780	1.07	.98	1.02	.95	1.03	1.01	.98	.98	1.06	1.02	7	7	8	9	10	10	10	10	10	10
1790	1.00	.98	.97	1.02	1.03	.96	1.04	1.00	1.00	1.01	10	10	10	10	10	10	10	10	10	10
1800	.96	1.04	.95	.99	1.02	1.04	1.01	.98	1.01	.96	10	10	10	10	10	10	10	10	10	10
1810	1.07	.96	.94	1.03	1.09	.95	1.05	.01	1.07	.94	10	10	10	10	10	10	10	10	10	10
1820	1.09	1.02	.97	.96	1.03	.99	1.01	.98	.98	1.04	10	10	10	10	12	12	12	12	12	12
1830	.98	1.06	.89	1.02	1.06	1.09	.86	1.01	1.00	.98	12	12	13	12	12	12	11	12	11	11
1840	.97	1.06	1.01	1.01	.96	1.00	1.04	.98	.98	.97	11	11	11	10	11	11	11	10	10	10
1850	1.07	.95	1.05	.98	1.00	.93	1.08	.96	1.04	.99	10	10	10	9	9	9	9	9	9	9
1860	.99	1.02	1.04	.98	1.01	.94	1.00	.97	1.12	1.02	9	9	9	9	10	10	10	10	10	10
1870	.92	.98	1.02	1.00	1.00	.99	1.01	1.00	1.04	1.03	10	10	10	12	12	12	12	11	11	11
1880	.92	1.03	1.02	1.03	.93	.95	1.05	1.10	.91	1.04	12	13	13	14	14	14	14	15	15	16
1890	.90	.93	1.01	1.03	1.03	1.04	.98	1.00	.99	.91	16	16	16	16	16	16	16	16	16	16
1900	1.03	1.06	.96	1.01	1.02	.97	1.04	.96	.99	1.02	16	16	16	16	16	16	16	15	15	15
1910	.98	1.05	.93	1.03	1.01	1.06	1.01	.87	.91	1.16	15	14	14	14	14	14	14	14	14	14
1920	.98	1.00	1.02	.96	.99	1.01	1.06	.96	.98	.92	14	14	14	14	16	15	14	14	14	14
1930	1.04	1.02	1.08	1.00	.87	1.08	.93	1.10	1.01	.94	14	14	14	12	12	12	12	12	12	12
1940	1.02	1.01	.98	.92	1.00	.89	1.06	.97	1.09	.95	12	12	12	12	12	12	12	12	12	12
1950	.94	1.05	1.01	.97	1.00	1.04	.93	1.02	.95	1.04	12	11	11	10	10	10	7	7	6	6
1960	.97	1.06	.94	.90	.81	.96	1.33	1.12	.88	1.00	4	3	3	3	1	1	1	1	1	1
1970	1.00	1.00									1	1								

APPENDIX 1: (Cont'd)

HUDSON BAY ALL-SPECIES COMPOSITE RING WIDTH "C" CHRONOLOGY
YEARS: 1656 1981

TREE RING INDICES

DATE	0	1	2	3	4	5	6	7	8	9
1650							.91	1.11	.97	1.01
1660	1.05	.96	.90	1.07	1.08	.98	.86	1.10	.91	.79
1670	1.22	1.00	.90	.89	1.03	.98	1.07	1.06	.94	.91
1680	1.05	.98	1.04	.93	.95	1.12	1.05	.96	.92	1.04
1690	1.06	.96	1.02	1.00	.94	1.00	1.09	.89	.89	1.07
1700	.98	.97	1.07	1.00	.94	.94	1.00	1.05	.95	1.01
1710	.97	1.06	1.05	.96	.87	1.04	.99	1.14	.81	1.06
1720	.99	1.07	.90	1.02	.92	1.03	1.01	1.08	1.01	1.03
1730	.98	.96	.93	1.09	1.00	.89	1.08	.95	.95	1.03
1740	.96	1.03	1.07	1.00	.94	1.03	.99	1.01	.93	1.02
1750	.90	1.12	1.00	.93	1.01	.92	.99	1.12	.96	.93
1760	.98	.80	1.04	1.22	.86	.93	1.03	.87	1.08	1.08
1770	1.02	1.00	.95	1.01	.95	1.03	.98	.96	.92	.90
1780	1.06	1.01	1.12	.84	1.03	.97	.84	1.00	1.11	1.04
1790	1.04	1.03	.94	.98	.99	1.00	.93	1.09	.89	1.17
1800	.81	.95	.98	1.00	1.01	1.08	.98	1.10	.98	.93
1810	1.03	.95	.90	.94	1.10	1.16	.81	.90	.83	1.04
1820	1.04	1.06	1.09	.98	.82	.80	1.17	.90	1.01	.99
1830	1.02	.92	1.04	1.05	1.11	.92	1.04	.86	1.02	1.03
1840	.99	1.05	1.07	.88	.94	1.00	1.06	.96	.90	1.05
1850	1.05	.96	1.00	1.00	1.07	.97	1.07	.91	1.04	.95
1860	.91	1.01	.96	1.30	1.08	1.01	.93	.99	1.14	.82
1870	1.05	.93	.97	.99	1.05	1.00	.97	1.04	1.05	.90
1880	.97	.96	1.06	1.02	.97	.98	1.00	1.12	1.00	.91
1890	.96	.99	.98	1.04	.99	1.10	.95	.96	.95	.94
1900	1.06	.97	.98	1.03	.97	1.00	1.01	1.01	1.01	1.01
1910	.99	1.03	.90	1.04	1.04	.92	.97	1.09	.99	1.04
1920	.87	1.00	.95	1.05	1.02	1.03	.94	.95	1.02	.95
1930	1.01	.99	1.04	.96	1.00	1.13	.89	.94	.96	1.00
1940	.99	1.03	.97	.96	.99	.90	1.10	1.02	1.14	.89
1950	.86	1.11	.89	1.06	1.05	1.04	.82	1.07	.90	1.13
1960	1.01	.98	.97	1.14	.80	.90	1.15	1.03	.94	1.07
1970	.97	.93	1.10	.95	1.04	.98	.97	.93	1.11	1.08
1980	.60	1.19								

NUMBER OF RADII

0	1	2	3	4	5	6	7	8	9
						1	1	1	1
1	1	1	1	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	4	4	4	4	4	4	4	4	4
4	4	4	4	4	4	4	4	4	4
6	6	6	6	6	6	6	6	7	7
7	7	8	8	8	8	8	8	9	9
10	10	10	10	10	10	10	10	11	11
12	11	12	12	12	13	13	13	13	13
13	13	13	13	13	13	13	13	13	13
14	14	14	14	14	14	14	13	13	13
15	15	15	15	16	16	16	16	16	16
18	18	18	18	18	18	18	18	18	18
19	19	20	21	22	22	22	22	22	22
24	24	24	24	24	24	24	24	24	24
25	25	25	25	25	25	25	25	25	25
25	25	25	25	25	25	25	25	25	25
25	25	25	25	27	27	27	27	27	27
27	27	28	27	27	27	26	27	26	26
26	26	26	25	26	26	26	25	25	25
26	26	26	25	25	25	25	25	25	25
25	25	25	25	26	26	26	26	26	26
27	27	27	29	29	29	29	28	28	28
29	30	30	31	31	31	31	32	32	33
33	35	35	39	41	43	44	44	44	44
47	48	50	50	49	49	49	48	50	50
52	51	51	51	51	53	53	53	53	53
53	53	53	53	55	54	53	53	53	53
53	53	53	51	51	51	51	51	51	51
51	51	51	51	51	51	51	51	51	51
50	48	48	47	47	47	44	44	43	43
41	40	40	40	38	38	38	37	37	37
37	37	36	36	36	36	35	35	20	20
20	19								

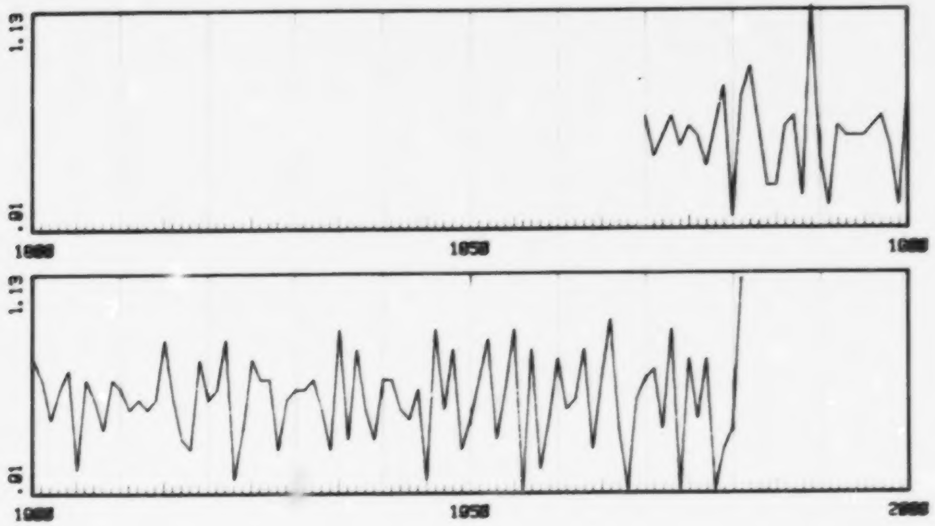
APPENDIX 1: (Cont'd)

HUDSON BAY ALL-SPECIES COMPOSITE MAXIMUM DENSITY "C" CHRONOLOGY
YEARS: 1656 1981

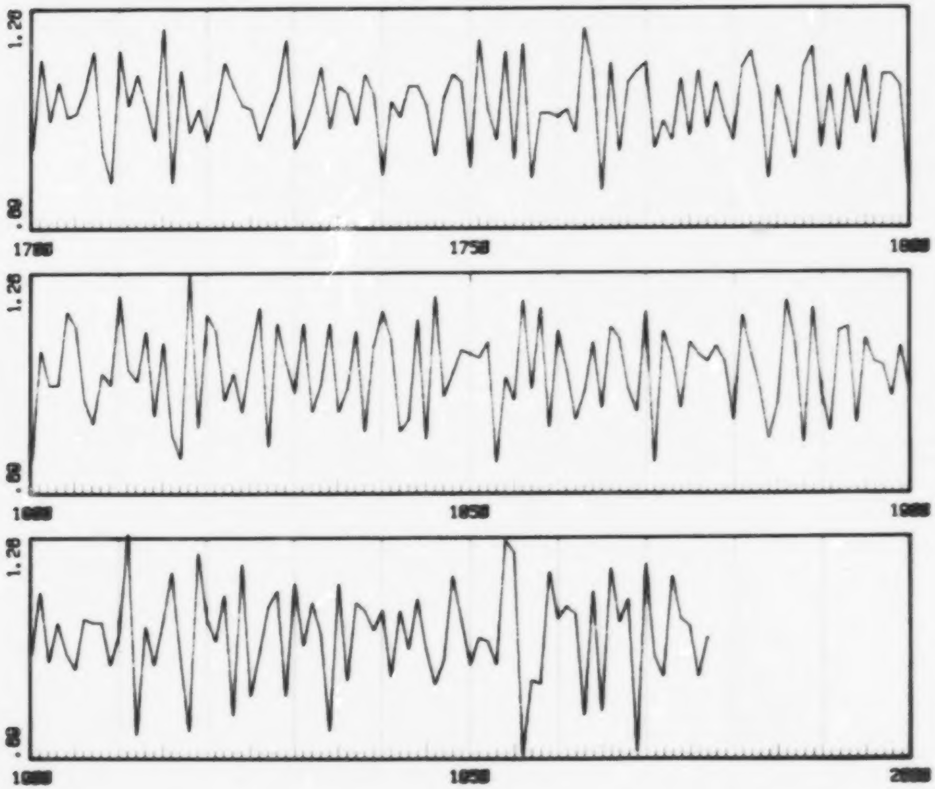
	TREE RING INDICES										NUMBER OF RADII									
DATE	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1650							1.03	1.04	.92	.95							1	1	1	1
1660	1.06	.96	1.03	1.03	.95	1.04	.99	1.02	1.02	1.00	1	1	1	1	2	2	2	2	2	2
1670	.95	1.01	1.03	1.04	.99	.90	1.01	1.01	.95	1.06	2	2	2	2	2	2	2	2	2	2
1680	1.00	1.01	1.02	.95	1.02	1.01	.99	1.00	.90	1.07	2	4	4	4	4	4	4	4	4	4
1690	.96	.94	1.03	1.04	1.02	.99	1.05	.90	.93	1.03	4	4	4	4	4	4	4	4	4	4
1700	.94	1.06	.96	1.06	.90	.90	1.05	1.04	.97	.91	6	6	6	6	6	6	6	6	7	7
1710	1.05	1.04	.99	1.04	.90	1.07	.95	1.05	.96	1.02	7	7	8	8	8	8	8	8	8	8
1720	.94	1.00	1.05	1.04	.90	.95	.99	1.01	1.02	1.05	10	10	10	10	10	10	10	10	11	11
1730	.95	.90	1.00	1.05	.96	1.04	.97	.97	1.07	1.03	12	11	12	12	12	13	13	13	13	13
1740	.85	1.00	1.00	1.04	1.01	1.03	.90	1.04	1.01	1.04	13	13	13	13	13	13	13	13	13	13
1750	.86	1.12	1.02	.99	1.07	.80	1.11	.89	.94	1.00	14	14	14	14	14	14	14	13	13	13
1760	.96	1.02	.97	1.13	1.00	.83	1.00	.93	1.03	1.07	15	15	15	15	16	16	16	16	16	16
1770	1.06	.94	.95	.94	1.00	.93	1.00	.95	1.03	.96	18	18	18	18	18	18	18	18	18	18
1780	.96	1.06	1.00	.99	.91	1.03	.97	.92	1.00	1.09	19	19	20	21	22	22	22	22	22	22
1790	.94	1.02	.92	1.05	.99	1.04	.96	1.05	1.05	1.05	24	24	24	24	24	24	24	24	24	24
1800	.84	1.05	.95	.97	1.10	1.09	.95	.91	1.00	.96	25	25	25	25	25	25	25	25	25	25
1810	1.15	.90	.96	1.07	.96	1.03	.92	.70	1.10	.89	25	25	25	25	25	25	25	25	25	25
1820	1.12	1.07	.94	.90	.95	1.01	1.10	.80	1.06	1.02	25	25	25	25	27	27	27	27	27	27
1830	.96	1.09	.90	.90	1.09	.90	.92	1.06	.91	1.02	27	27	28	27	27	27	26	27	26	26
1840	1.00	1.07	.91	.92	1.05	.89	1.13	.96	.99	1.02	26	26	26	25	26	26	26	25	25	25
1850	1.05	1.00	1.06	.84	.99	.92	1.15	.95	1.12	.90	26	26	26	25	25	25	25	25	25	25
1860	1.05	1.01	.93	.96	1.04	.91	1.07	1.04	1.02	.94	25	25	25	25	26	26	26	26	26	26
1870	1.06	.85	1.07	1.02	.95	1.03	1.02	1.01	1.05	1.03	27	27	27	29	29	29	29	28	28	28
1880	.89	1.09	1.03	.90	.87	.93	1.12	1.00	.86	1.10	29	30	30	31	31	31	31	32	32	33
1890	.96	.80	1.05	1.06	.96	1.05	1.00	1.01	.97	.97	33	35	35	39	41	43	44	44	44	44
1900	1.01	1.07	.95	1.02	1.00	.94	1.03	1.00	1.00	.99	47	48	50	50	49	49	49	48	50	50
1910	1.00	1.10	.89	1.01	.90	1.05	1.05	.93	.87	1.13	52	51	51	51	51	53	53	53	53	53
1920	1.01	1.00	1.06	.89	1.04	.97	1.01	1.02	1.01	.93	53	53	53	53	55	54	53	53	53	53
1930	1.06	1.00	1.05	.99	.86	1.09	.93	1.07	1.02	.97	53	53	53	51	51	51	51	51	51	51
1940	1.04	.97	1.01	.96	1.05	.92	1.00	.97	1.09	.90	51	51	51	51	51	51	51	51	51	51
1950	.95	1.02	1.02	.95	1.09	1.11	.83	.90	.91	1.06	50	48	48	47	47	47	44	44	43	43
1960	1.04	1.02	1.02	.93	1.01	.92	1.13	1.00	.99	.87	41	40	40	40	38	38	38	37	37	37
1970	1.09	.99	.93	1.11	.97	1.03	.94	1.02	.91	.95	37	37	36	36	36	36	35	35	20	20
1980	.97	1.12									20	19								

APPENDIX 1: (Cont'd)

Churchill River Black Spruce

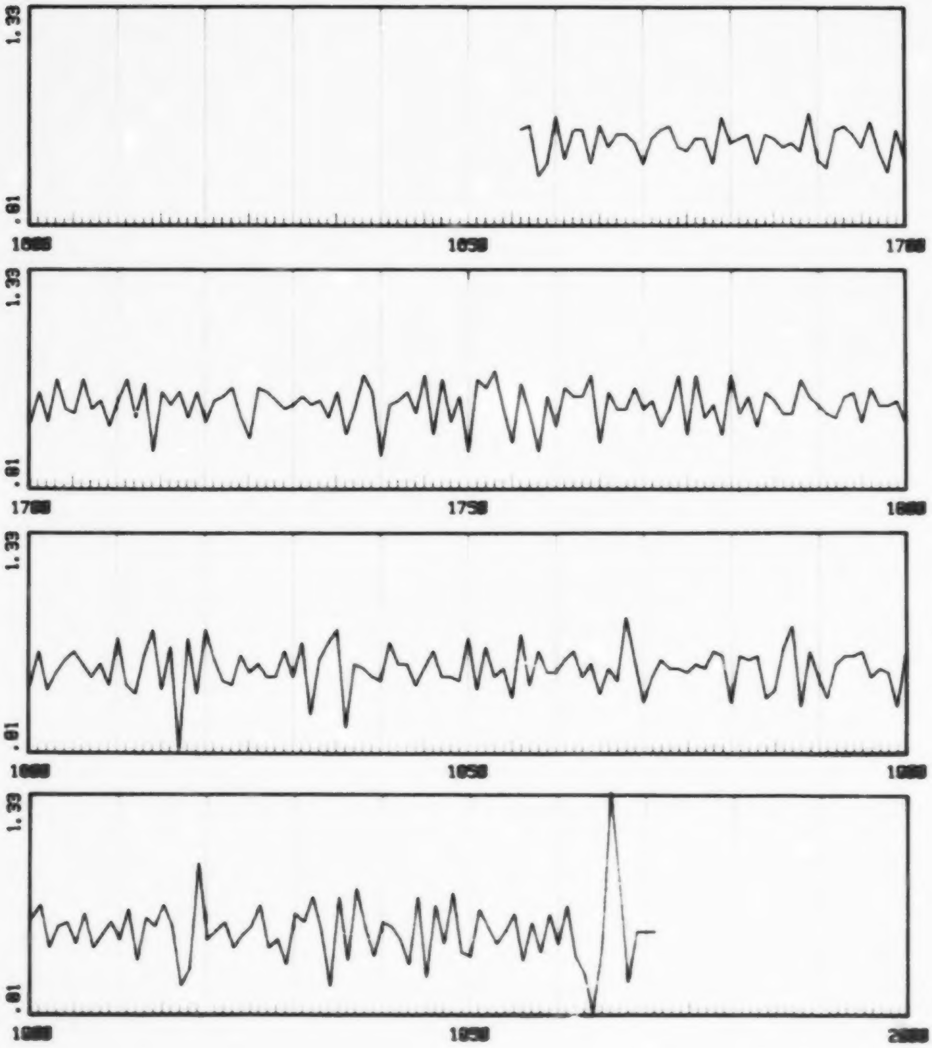


Cri Lake White Spruce



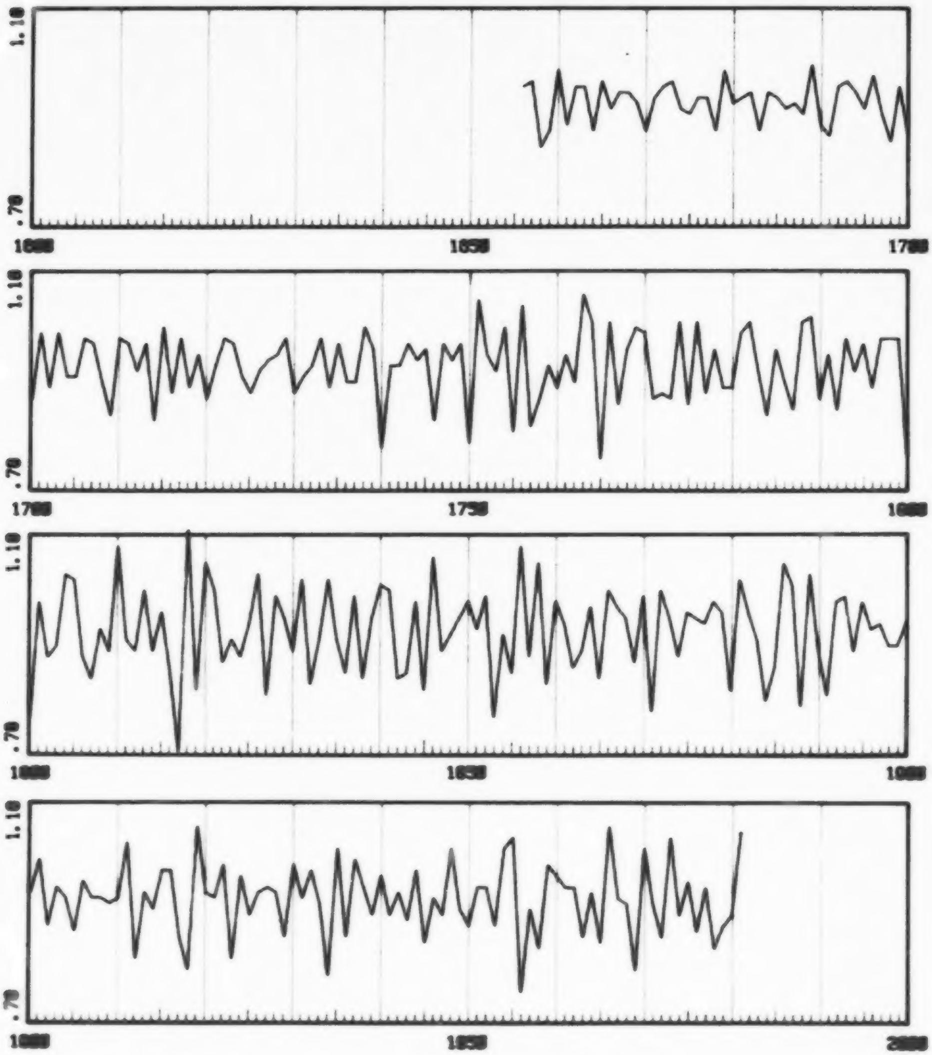
APPENDIX 1: (Cont'd)

Hudson Bay Driftwood Composite

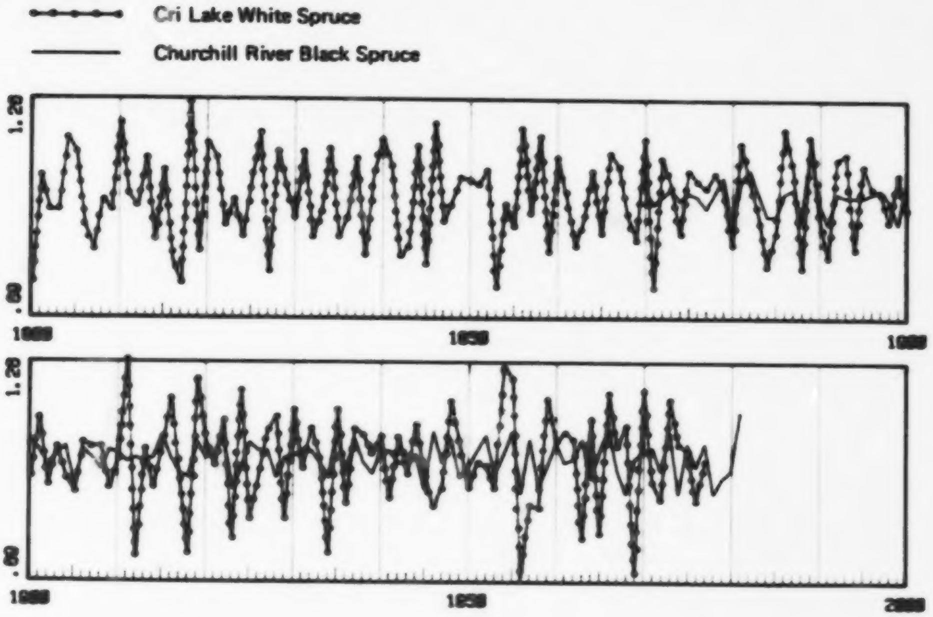


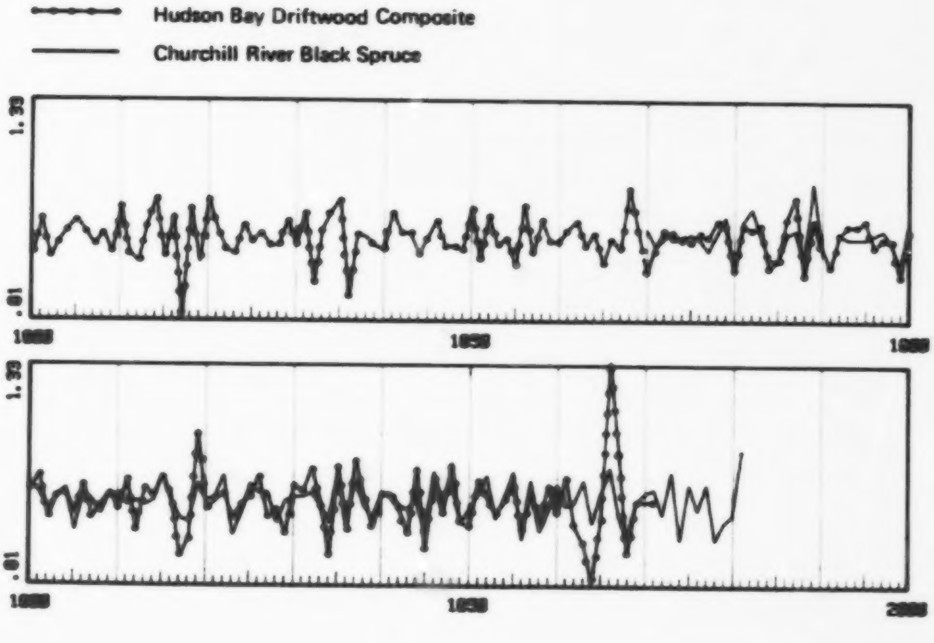
APPENDIX 1: (Cont'd)

Hudson Bay Living-tree and Driftwood Composite

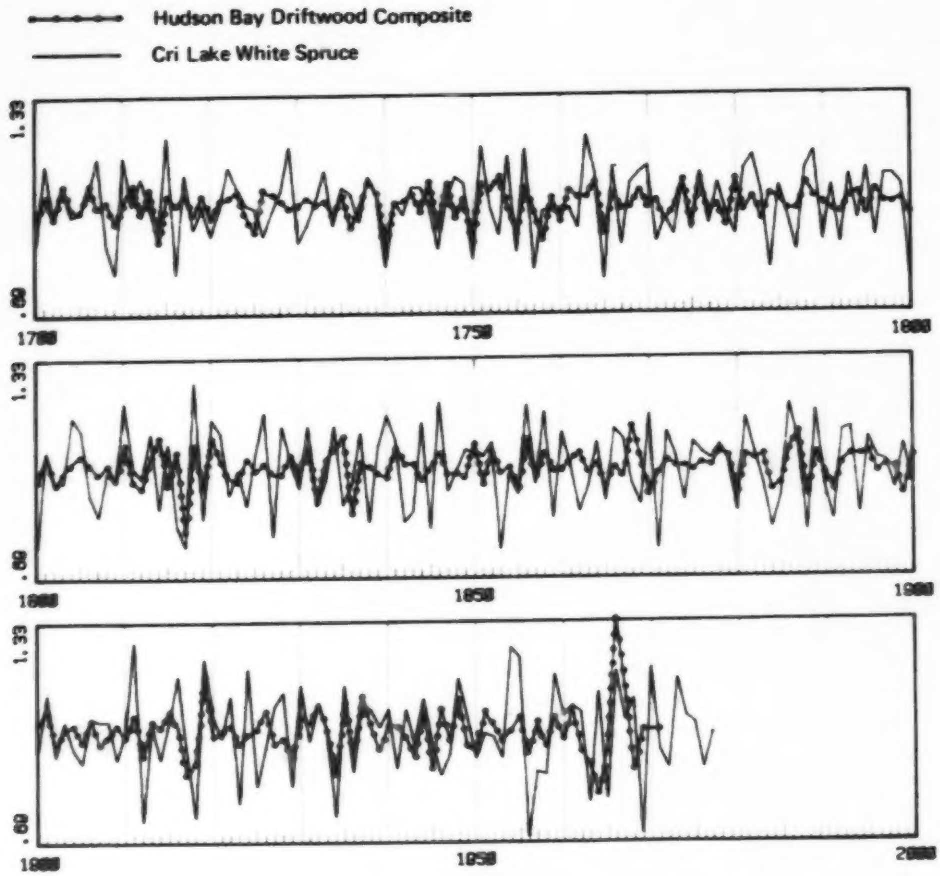


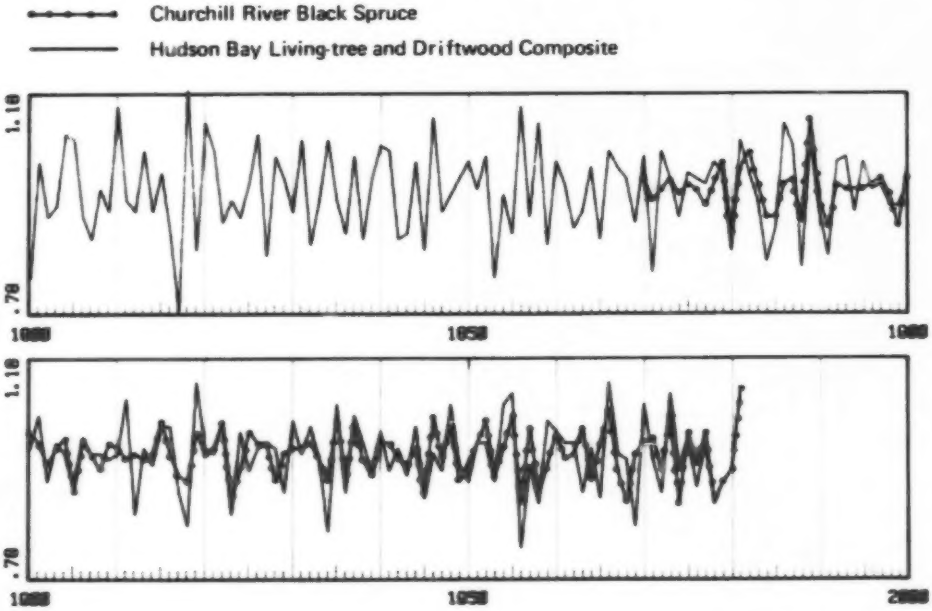
APPENDIX 2: *BROKEN-LINE PLOTS SHOWING CROSSDATING BETWEEN COMPOSITE DRIFTWOOD AND LIVING-TREE CHRONOLOGIES. ALL SERIES ARE MAXIMUM RING DENSITY OF THE "C" TYPE.*



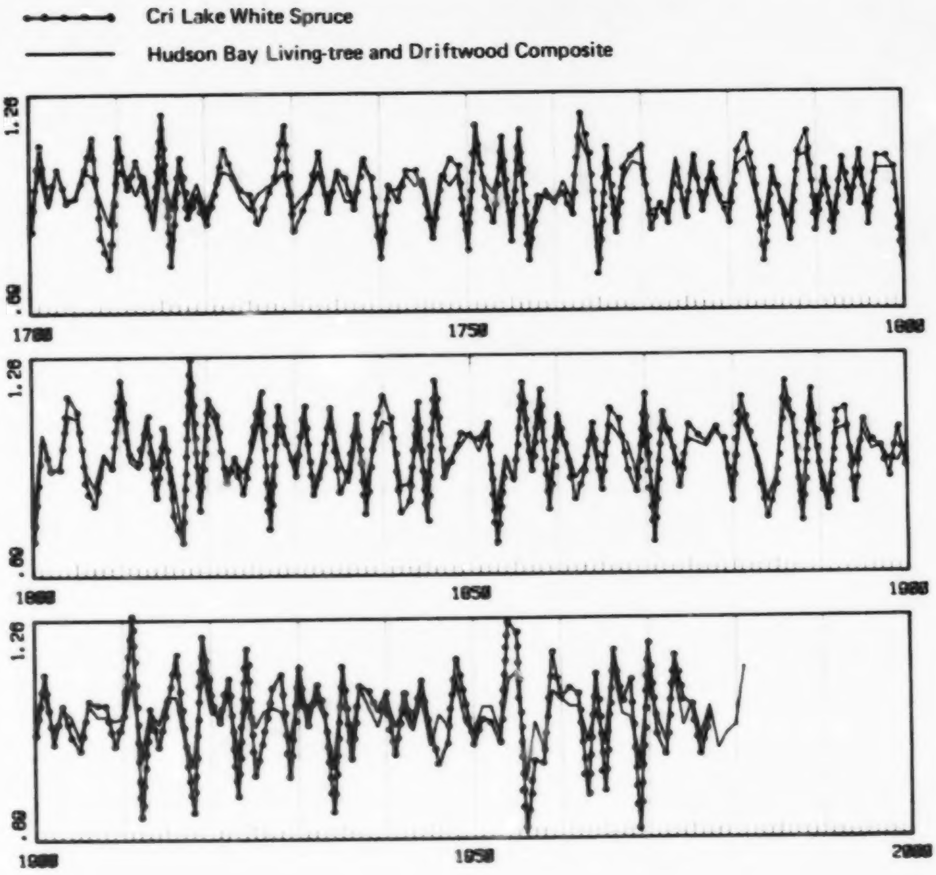


APPENDIX 2: (Cont'd)

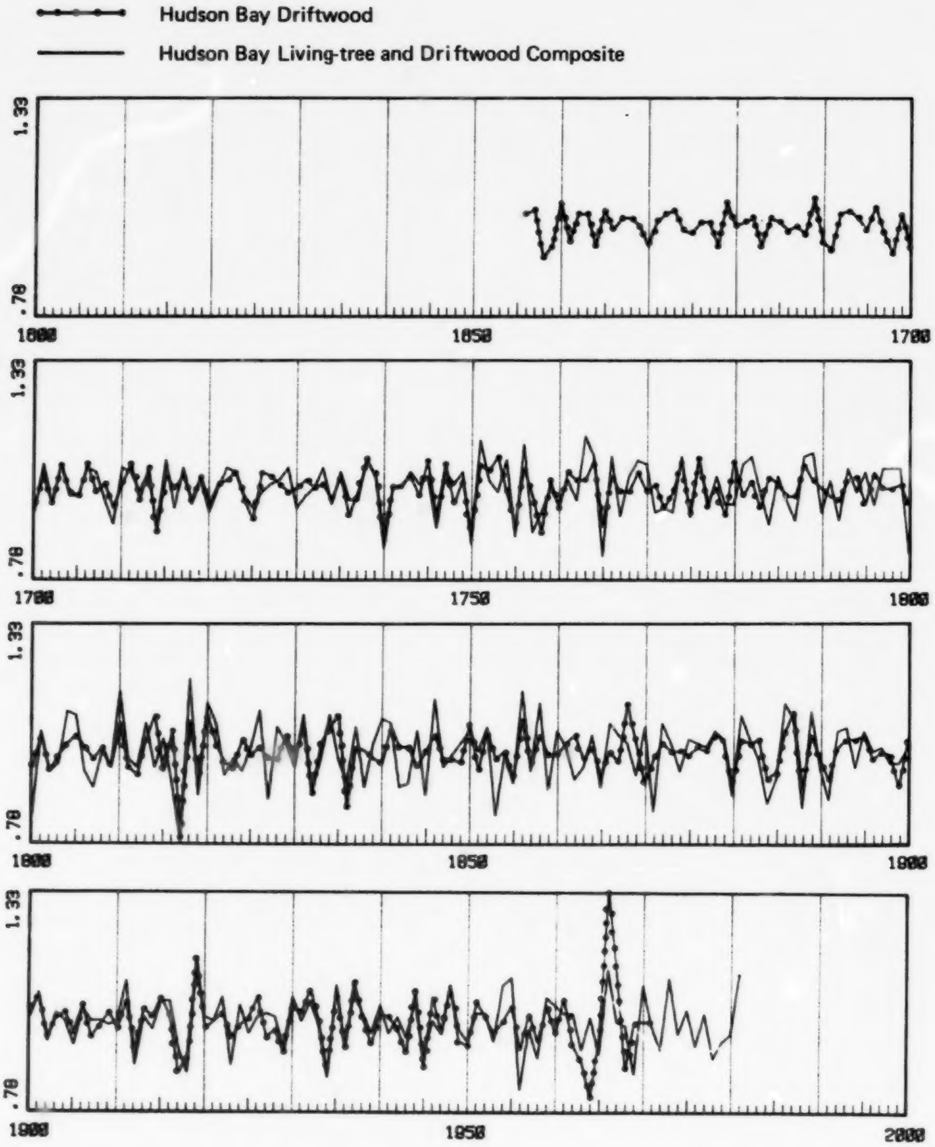




APPENDIX 2: (Cont'd)



APPENDIX 2: (Cont'd)



A MAPPED HISTORY OF HOLOCENE VEGETATION IN SOUTHERN QUÉBEC

Thompson Webb III,[1] Pierre J.H. Richard,[2] and Robert J. Mott[3]

INTRODUCTION

Maps of Holocene pollen data reveal the former patterns in the source vegetation for the pollen. With careful analysis, the maps can show the changing location and composition of past vegetational regions. The size of the vegetational patterns resolved depends upon such characteristics of the data set as its geographic extent, density of sampling sites, and the type and size of basins sampled. Different choices among these characteristics can allow the maps to depict vegetational changes from the scale of formations down to the scale of woodland stands. Climatic change affects all of these scales of vegetational patterns, and records of the changing patterns at more than one scale can aid climatic interpretation of the data.

Bernabo and Webb (1977) used a grid of 60 radiocarbon-dated pollen diagrams to map the vegetational patterns within 1 million sq. km of eastern North America. Their maps illustrated major vegetational changes in composition and location at the formation level. Ritchie (1976), with a different data set, illustrated changes at this same scale in north-central North America. Other studies at the subcontinent scale include those of Davis (1976, 1981A) and Delcourt and Delcourt (1981) in eastern North America, Huntley and Birks (1983) in Europe, and Neustadt (1958), Khotinskii (1977), and Peterson (1983) in the Soviet Union. From these studies, a picture is emerging of the long-term, broad-scale vegetational changes. The need now exists to examine the changing vegetational patterns over smaller areas and to show how differences in topography and soils affect the broad-scale changes described in Bernabo and Webb (1977), Davis (1981A), Delcourt and Delcourt (1981), and Ritchie (1976).

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Szafer (1935) and Firbas (1949) were the first to produce isopoll maps from 300,000 to 500,000 sq. km regions, but their studies were done without the benefits of radiocarbon dates. Since the use of radiocarbon dates, Birks *et al.* (1975) and Birks and Saarnisto (1975) have produced isopoll maps for Britain and Finland; and Davis and Jacobson (in press) have recently used the data from a grid of pollen diagrams to map the late-glacial vegetation in northern New England. Our study complements this later work by mapping the Holocene pollen data from a network of 44 sampling sites within 176,000 sq. km of southern Québec (Mott 1977; Richard 1977; Savoie and Richard 1979; Gauthier 1981; Labelle and Richard 1981; Comtois 1982; Richard, unpublished). With a site density of 1 site/ 4,000 sq. km, our maps reveal how the vegetational history in the St. Lawrence Valley differs from the history recorded at sites in the uplands to the north and south of the valley. Within the valley, the contrasting patterns from Montréal northeastward to Québec City are also illustrated.

Richard (1977) and Mott (1977) have already shown that southern Québec is an excellent region in which to examine the late-Holocene southward increase in coniferous forest conditions. This change indicates climatic cooling during the past 4,000 years. Other significant vegetational changes within southern Québec include the initial appearance of coniferous forest trees north of the St. Lawrence River Valley about 10,000 yr B.P., the disappearance of treeless vegetation after 8,000 yr B.P., and several compositional changes within the mixed forest (Richard 1977). Maps of these vegetational changes will aid their interpretation in terms of the sequence of Holocene climatic changes.

Physiographic Provinces and Modern Vegetation of Southern Québec

The study area (Figure 1) contains three physiographic provinces (Richard 1981B): the Laurentide Highlands in the north, the Appalachian Highlands in the southeast, and the St. Lawrence Lowlands in between. The Saguenay-Lake St. John Lowlands are a part of the Laurentide Highlands in the northeast. The elevation varies from sea level to slightly over 1,000 m (Figure 1).

Continent-wide vegetational maps (Rowe 1972) show that the southern border of the boreal forest (dominated by *Picea* and *Abies* trees) bisects southern Québec and lies just north of the St. Lawrence Valley. Vegetation types of the mixed conifer-hardwood

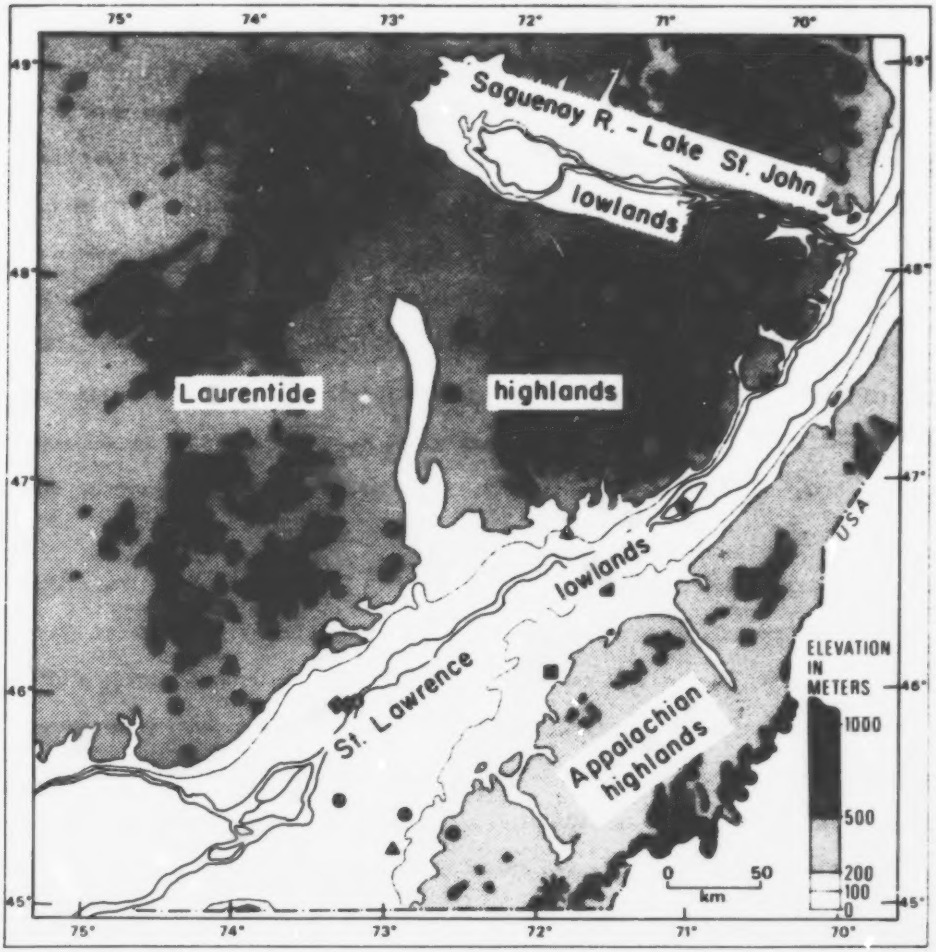
75°
74°
73°
72°
71°
70°
49°
48°
47°
46°
45°
Saguenay R. - Lake St. John
lowlands
Laurentide
highlands
St. Lawrence
lowlands
Appalachian
highlands
USA
ELEVATION
IN
METERS
1000
500
200
100
0
0
50
km

FIGURE 1: *Physiographic provinces in southern Québec (from Richard 1981A).*

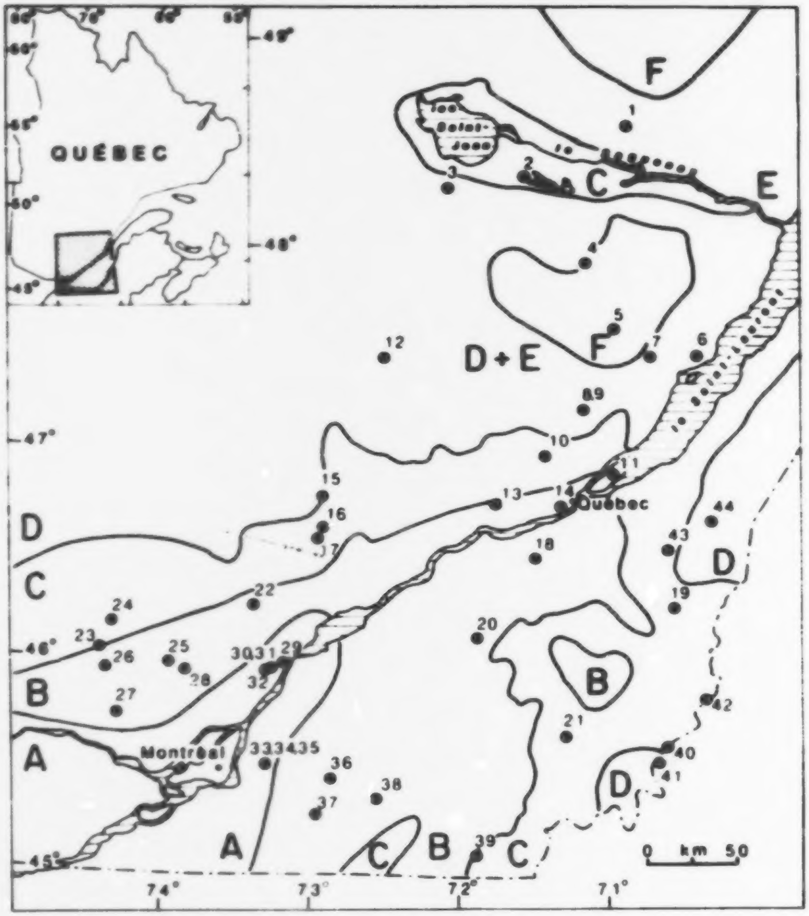
QUÉBEC
Lac Saint-Jean
Québec
Montréal
F
C
E
D+E
F
D
C
B
A
D
B
D
A
C
B
C
1
2
3
4
5
6
7
8 9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30 31
32
33 34 35
36
37
38
39
40
41
42
43
44
47°
46°
45°
74°
73°
72°
71°
0 km 50

FIGURE 2: *Vegetation regions in southern Québec and Maine and the location of the 44 radiocarbon-dated pollen diagrams. The mixed conifer-hardwood forest is subdivided into: (A)* Caryo-Aceretum, *(B)* Aceretum sacchari, *and (C)* Betulo-Aceretum *forests; and the boreal forest is subdivided into (D)* Betulo luteae-Abietetum, *(E)* Betulo papyriferae-Abietetum, *and (F)* Piceetum *forests with open spruce woodlands (*Taïga*) at high elevations in the* Piceetum *region. The location of the vegetational regions is adapted from Granditner (1966).*

forest grow within the valley and at moderate elevations to the south of the valley. Outliers of the boreal forest also occur south of the valley in isolated highland regions (above 500 m), and mixed forests of *Betula lutea* and *Acer* trees grow in the Saguenay-Lake St. John Lowlands, well to the north of the valley.

Vegetation maps for just southern Québec show that the mixed conifer-hardwood forest can be divided into three regions and the boreal forest can be divided into four regions (Figure 2). Within the mixed forest, maple forests with hickories and oaks *(Caryo-Aceretum)* grow in the southwest, sugar maple forests with basswoods, elms, and ashes *(Aceretum saccahri)* extend northeastward down the valley to Québec City, and maple forests with yellow birches *(Betulo-Aceretum)* grow north of the valley, in the Saguenay-Lake St. John Lowlands, and in the southeast. Major species growing in these forests include *Acer rubrum*, *A. saccharum*, *Betula lutea*, *Fagus grandifolia*, *Fraxinus pennsylvanica*, *F. americana*, *F. nigra*, *Ostrya virginiana*, *Pinus strobus*, *P. resinosa*, *Quercus rubra*, *Thuja occidentalis*, *Tilia americana*, *Tsuga canadensis*, and *Ulmus americana* (Richard 1977). Minor but constant species are *Carya ovata*, *C. cordiformis*, *Juglans cinerea*, and *Quercus macrocarpa*.

Within the boreal forest, the four regions include: (1) fir forests with yellow birch *(Betulo luteae-Abietetum)* which grow both south and north of the valley; (2) fir forests with white birch *(Betulo papyriferae-Abietetum)* which grow in the Laurentides between 500 and 750 m; (3) spruce forests *(Piceetum)* which grow in the Laurentides over 750 m; and (4) open spruce woodlands *(Taïga)* which represent patches on the most xeric sites within the spruce forests in the Laurentides. Major species (not named previously) growing in these forests include *Abies balsamea*, *Betula papyrifera*, *Larix laricina*, *Picea glauca*, *P. mariana*, *P. divaricata (banksiana)*, and *Populus tremuloides*. *Populus balsamifera* and *Fraxinus nigra* are minor species, and *Picea rubens* is a rare species in the southeastern part of the Laurentides, but grows well and is abundant in the Appalachians.

In the St. Lawrence Valley, most of the land was cleared of forest and only remnants of the primeval forests were not cut. Today, successional forests with *Acer rubrum*, *Betula papyrifera*, *B. populifolia*, and *Populus tremuloides* dominate many of the forest stands within this region.

Appendix 1 shows how the contemporary pollen data from sediment samples record the modern vegetation. Isopoll maps are presented that contain the contours that appear on the isochrone maps produced from the Holocene data.

DATA AND METHODS

The Data Set

The study area (Figure 1) lies between 45°N (Barnston) and 48°40'N (Mont Valin) and between 70°20'W (Lac Mimi) and 74°30'W (St. Agathe). One hundred and sixty eight radiocarbon dates were available among the 44 sites, and except for Princeville at least one radiocarbon date was available from each of the sites (Table 1). Most of the cores come from small lakes; only 13 bogs are included in the data set. Webb *et al.* (1978B) have shown that the surface pollen spectra from lake sediments and peats yield similar maps of the upland vegetation and that data from both sediment types can therefore and used to increase the coverage and density of sites with a data set.

The data from each site were stored in computer files, with the pollen data in one file and the chronological data (dates and their depths) in one to several separate "chron" files. The first chron file for each site contains all available radiocarbon dates plus estimated dates for the top of the core (usually set at 0 yr B.P.) and for the depth of the *Ambrosia* rise (150 ± 50 yr B.P.), if one exists. Additional chron files were created for each site in order to accommodate corrections to available dates, dates for pollen-stratigraphic events (e.g., *Tsuga* decline (Davis 1981B)), or deletions of dating reversals. These files provided the raw material for estimating a date of each pollen spectrum at each site. Notes within each additional chron file document fully any corrections, additions, or deletions to the data available in the first chron file.

Data Analysis

All data analysis was done on the computer except for the final step of drawing the contours on the isopoll and isochrone maps. The computer analysis included selection of the pollen data from storage files, calculation of pollen percentages, estimation of dates for each pollen sample, interpolation of pollen percentages for the dates to be mapped, and a printout of these pollen percentages on maps. Use of the computer guaranteed uniform analysis of the data from all sites.

A sum of all tree, shrub, and herb pollen was used to calculate the pollen percentages in each sample. Only spores and pollen from aquatic plants (e.g., *Nuphar* and *Typha*) were excluded from the sum.

1. *Assignment of Dates to Depths in Cores*

Analysis of the chronological data began with plotting scatter diagrams of the depths and dates in each chron file. These plots aided the choice of which chron file to use at each site. Once a chron file was selected, we linearly interpolated between adjacent radiocarbon or stratigraphically-assigned dates and estimated a date for each depth with a pollen sample. For sites with six or more dates, more sophisticated age models can be used (Ogden 1977; Overpeck and Fleri 1982), but they were not used in this study for the sake of uniformity of data analysis among all sites.

To gain the mapped pollen values at each site, the critical choice was the set of radiocarbon and/or stratigraphically-assigned dates used for linearly interpolating the date at each pollen sample. For 24 of the 44 sites, radiocarbon dates from the sediments at the site were sufficient for estimating the dates. At five sites (Ange, Tortue, St-Germain, St-Francois-de-Sales, and Lac Mimi), minor dating reversals were removed prior to linear interpolation. In addition, the *Tsuga* decline (4,700 ± 200 yr B.P. (Davis 1981B; Webb 1982)) was used at both Tortue and Lac Mimi as well as at 10 other sites. At the remaining five sites (Princeville, Terrien, Bouleaux, Boundary, and Unknown), the dating for the entire Holocene was adjusted by using dates from nearby sites for two or more pollen-stratigraphic events.

Princeville had no radiocarbon dates, and was dated by using a date for the *Tsuga* decline and a 9,000 ± 300 yr B.P. date for the *Picea* decline, as dated at nearby sites. Terrien and Bouleaux only had dates of 12,000 yr B.P. and older, which made it difficult to interpolate accurately the dates for Holocene events, especially at Bouleaux from Mt.-St.-Bruno (Figure 2). The dates from Lac Colin were used at Terrien, and the dates from Yamaska were used at Bouleaux. Both Lac Colin and Yamaska are well-dated sites. Subsequent to this choice of dates, two new sites (Tortue and Atocas) from Mt.-St.-Bruno were added to the data set, and the dates from these sites supported the use of the Yamaska dates at Bouleaux (Table 1).

TABLE 1: *LOCATIONAL AND DATING INFORMATION FOR SITES WITH POLLEN DATA.*

SITE NAME	LATITUDE (N)	LONGITUDE (W)	ALTITUDE (M)	SITE TYPE (LAKE= L) (BOG= B)	SIZE (HA)	WATER DEPTH (M)	NUMBER OF RADIOCARBON DATES	ESTIMATED AGE FOR TOP OF CORE (YR B.P.)	OLDEST RADIOCARBON DATE (YR B.P.)	REFERENCE
1 Mont Valin	48 36	70 50	841	L	0.5	0.5	4	100	9920	Richard (unpublished)
2 Kenogami	48 22	71 34	166	B	0.5	---	5	0	7630	Richard (1977)
3 St Francois de Sales	48 18	72 09	358	L	2.0	1.1	3	0	8955	Richard (unpublished)
4 Montagnais	47 54	71 10	800	B	10.0	---	1	200	8510	Richard (1977)
5 Malbaie	47 36	70 58	800	B	120.0	---	2	0	8095	Richard (1977)
6 Lac Mimi	47 30	70 23	411	L	10.0	4.0	6	300	11050	Richard (1977)
7 Baie St Paul (Ange)	47 29	70 41	640	L	0.5	3.0	7	0	10710	Labelle and Richard (1981)
8 Joncas Bog	47 15	71 10	747	B	2.0	---	2	0	7140	Richard (1971,1977)
9 Joncas Lake	47 15	71 11	780	L	5.0	2.7	1	50	8120	Richard (unpublished)
10 Marcotte	47 05	71 25	503	L	3.8	1.3	5	0	9885	Labelle and Richard (1981)
11 St Jean, Ile D'Orleans	46 56	70 56	68	B	150.0	---	3	0	6100	Richard (1971,1977)
12 Martini	47 28	72 46	242	L	2.0	5.0	4	0	8740	Richard (unpublished)
13 St. Raymond	46 53	71 48	160	B	100.0	---	2	0	7970	Richard (1977)
14 Bog Ste-Foy	46 47	71 20	16	B	55.0	---	2	0	5540	Larouche (unpublished)
15 Mauricie	46 48	72 59	405	B	1.0	---	5	50	9670	Richard (1977)
16 Sam	46 39	72 59	240	L	1.0	5.3	6	100	9350	Richard (unpublished)
17 Castor	46 37	73 00	220	L	1.0	0.7	6	0	9540	Richard (unpublished)

TABLE 1: *LOCATIONAL AND DATING INFORMATION FOR SITES WITH POLLEN DATA.* (Cont'd)

SITE NAME	LATITUDE (N)	LONGITUDE (W)	ALTITUDE (M)	SITE TYPE (LAKE= L) (BOG= B)	SIZE (HA)	WATER DEPTH (M)	NUMBER OF RADIOCARBON DATES	ESTIMATED AGE FOR TOP OF CORE (YR B.P.)	OLDEST RADIOCARBON DATE (YR B.P.)	REFERENCE
18 Dosquet	46 27	71 30	139	B	200.0	---	1	0	8835	Richard (1977)
19 Benjamin	46 17	70 36	330	L	30.0	0.8	1	0	9100	Richard (1977)
20 Princeville	46 08	71 56	135	L	2.5	0.3	0	3000	(9000)	Richard (1977)
21 Albion	45 40	71 19	320	L	2.5	3.0	4	50	10880	Richard (1977)
22 Gabriel	46 17	73 29	250	L	3.0	0.75	5	100	9105	Richard (1977)
23 St Agathe	46 03	74 28	454	L	2.0	2.8	3	0	10170	Savoie and Richard (1979)
24 Aux Quenouilles	46 10	74 24	403	L	2.0	1.95	3	0	10820	Savoie and Richard (1979)
25 Gea-I	45 59	74 00	365	L	1.0	6.5	1	0	10140	Richard (unpublished)
26 St Germain	45 57	74 22	473	L	5.0	6.2	6	0	10420	Savoie and Richard (1979)
27 Tania	45 46	74 18	305	L	2.0	4.0	6	100	10000	Richard (unpublished)
28 St Calixte	45 58	73 52	261	L	1.7	1.25	4	0	9755	Richard (unpublished)
29 Lanoraie	46 00	73 13	20	B	> 200.0	---	4	0	4730	Richard (unpublished)
30 Joseph	45 59	73 18	18	B	> 100.0	---	3	0	4790	Comtois (1979)
31 Henri	45 59	73 18	19	B	5.0	---	6	100	5960	Comtois (1979)
32 Romer	45 58	73 20	18	L	6.0	---	4	0	6920	Comtois (1979)
33 Atocas	45 32	73 19	114	L	1.0	0.8	4	100	10250	Gauthier (1981)
34 Tortue	45 33	73 19	136	L	2.5	7.0	4	0	9215	Gauthier (1981)

TABLE 1: *LOCATIONAL AND DATING INFORMATION FOR SITES WITH POLLEN DATA.* (Cont'd)

	SITE NAME	LATITUDE (N)	LONGITUDE (W)	ALTITUDE (M)	SITE TYPE (LAKE= L) (BOG= B)	SIZE (HA)	WATER DEPTH (M)	NUMBER OF RADIOCARBON DATES	ESTIMATED AGE FOR TOP OF CORE(YR B.P.)	OLDEST RADIOCARBON DATE(YR B.P.)	REFERENCE
35	Bouleaux	45 33	73 19	130	L	13.3	7.9	2	150	13000	Mott (1977)
36	Yamaska	45 27	72 52	265	L	2.0	3.5	7	0	10260	Richard (unpublished)
37	Farnham	45 17	72 59	53	B	>200.0	---	4	300	8150	Richard and Larouch (unpublished)
38	Shefford	45 22	72 35	282	B/L[1]	5.0	---	10	200	11400	Richard (1977)
39	Barnston	45 07	71 53	415	L	7.1	0.6	1	9800	11020	Mott (1977)
40	Unknown	45 36	70 38	489	L	7.5	2.1	4	0	14900	Mott (1977)
41	Boundary	45 34	70 40	603	L	24.0	5.9	5	0	11200	Mott (1977)
42	Dufresne	45 51	70 21	650	L	16.9	6.1	6	0	11200	Mott (1977)
43	Terrien	46 35	70 36	404	L	9.0	1.5	1	0	12640	Mott (1977)
44	Colin	46 43	70 17	658	L	16.9	6.1	8	0	11100	Mott (1977)

[1] B/L = a bog that developed from a lake with peat overlying lake sediments.

The Holocene dates at Boundary and Unknown Ponds, which are neighboring sites, differ for the same events. Some of their dates also differ from those at nearby Dufresne, which is an especially well-dated site (Table 1). A simplifying assumption was made that the dates for the rise in *Picea*, the decline in *Picea*, and the *Tsuga* decline were the same at all three sites, and the dates from Dufresne for these events were used at Boundary and Unknown. The adjustment of the dates at these five sites does not affect the regional patterns on the maps but avoids local anomalies that are difficult to contour.

The date for the *Tsuga* decline at about 4,700 yr B.P. was imposed at 12 sites in which the radiocarbon dates from the site placed the *Tsuga* decline either before 5,000 yr B.P. (Benjamin, 5,000 yr B.P.; GEA-I, 5,300 yr B.P.; Martini, 6,000 yr B.P.; Lac Mimi, 5,000 yr B.P.; St-Calixte, 5,500 yr B.P.; St.-Agathe, 6,100 yr B.P.; Aux Quenouilles, 5,800 yr B.P.; Tania, 5,200 yr B.P.; and Tortue, 5,200 yr B.P.) or after 4,000 yr B.P. (Farnham, 3,800 yr B.P.; Gabriel, 3,950 yr B.P.; and St.-Henri, 3,902 yr B.P.). Two factors influenced this decision: (1) data from 23 sites of the 38 sites with a *Tsuga* decline dated the event at 4,650 ± 300 yr B.P., a time that agrees well with dates for this event throughout the northeastern United States and southeastern Canada (Davis 1981B; Webb 1982); and (2) phytogeographic difficulties resulted if this dating constraint was not placed on the data set. The difficulties arose because the early dates for the *Tsuga*-decline (prior to 5,000 yr B.P.) also support an early date for the arrival of *Tsuga*. When these early dates are plotted on a map, *Tsuga* populations are shown arriving at isolated sites in the north (e.g., Martini; Figure 2) long before they arrive at sites in the St. Lawrence River valley. Such a migration pattern makes little phytogeographic sense, since the valley was completely open for plant colonization by 7,000 yr B.P. Use of a uniform date for the *Tsuga* decline eliminates this problem.

3. *Preparation of the Pollen Data for Mapping*

Tables of the pollen percentages for a total of 27 pollen types and three catch-all categories (Other trees, Other shrubs, and Other herbs) were printed as an interim step in producing the isopoll maps. Table 2 shows an example for Farnham Bog and presents the percentages for 13 pollen types and for both Other trees and Other shrubs. When all pollen types are included, the values on these tables sum to 100% for each spectrum. The pollen

TABLE 2. *COMPUTER-GENERATED LIST OF DEPTHS, DATES, AND POLLEN PERCENTAGES FOR FARNHAM BOG.*

```
SITE FARNHAM  IN QUEBEC;  LATITUDE = 45° 17' N. LONGITUDE = 72° 59' W. ELEVATION =   55  METERS.

              SPECTRUM DATES $                                       POLLEN PERCENTAGES
                                                                                                   OSTRYA/                                OTHER  OTHER
LEVEL DEPTH      1        2  $  PICEA  ABIES  PINUS BETULA  TSUGA  FAGUS   ACER  ULMUS FRAXIN.  CARP.  QUERCUS  CARYA JUGLANS  TREES  SHRUBS
***************************$*************************************************************************************************************
  1     0.0     300     300$   2.00   0.40  20.30  30.70  12.80  11.20   5.40   2.70   2.20   0.10    4.40    0.20   0.20    1.40   0.0
  2    10.0    1041     883$   1.60   0.10  20.00  31.70  15.90  11.30   3.40   2.40   3.90   0.0     3.30    0.40   0.0     1.20   0.0
  3    20.0    1782    1467$   0.90   0.0   23.70  27.50  13.80  12.10   5.80   2.00   5.20   0.0     3.20    0.0    0.40    0.70   0.0
  4    30.0    2524    2051$   1.90   0.40  19.70  32.20   6.60   8.90   5.20   3.10   3.30   0.0     7.50    0.70   0.10    1.50   0.10
  5    40.0    3265    2634$   1.40   0.20  30.40  27.10   4.90  14.00   2.90   0.60   3.90   0.20    5.70    0.40   0.0     1.80   0.0
  6    50.0    4006    3218$   1.30   0.30  18.60  40.90   4.20   8.80   4.20   3.30   3.40   0.0     4.70    0.30   1.00    2.30   0.0
  7    60.0    4643    3802$   2.40   0.0   15.80  30.10  13.90   9.80   5.50   6.40   3.20   0.0     4.70    0.40   0.20    0.90   0.0
  8    70.0    4861    4386$   1.70   0.30  13.40  38.50  12.80   9.30   6.10   2.60   6.40   0.0     3.80    0.0    1.20    0.60   0.30
  9    75.0    4970    4678$   4.80   0.0   11.30  26.80  19.40  11.10   3.50   3.30   3.30   0.0     6.10    0.30   0.0     6.30   0.70
 10    80.0    5079    4969$   1.70   0.0    8.10  21.10  11.30   7.80   3.90   3.30   3.80   0.20    5.10    0.20   0.30   27.90   1.40
 11    85.0    5272    5272$   0.90   0.10  14.70  26.30  20.50   6.70   2.60   3.30   2.30   0.0     7.50    0.20   0.10    4.90   3.30
 12    90.0    5590    5590$   1.50   0.40  28.10  22.60  11.10   1.50   2.90   3.80   2.70   0.0     7.30    0.40   0.0     8.70   2.40
 13   100.0    6226    6226$   2.10   0.10  37.50  10.40  13.30   0.40   2.10   3.90   3.20   0.10    8.70    0.10   0.0     1.50   0.0
 14   110.0    6707    6707$   0.70   0.0   70.70   7.40   1.90   0.50   0.70   3.70   1.90   0.50    4.40    0.0    0.0     1.60   0.50
 15   115.0    6869    6869$   1.90   0.70  66.70   7.00   4.70   1.20   0.70   1.60   0.90   0.0     3.80    0.0    0.0     1.40   0.0
 16   120.0    7032    7032$   8.80   0.30  65.00   8.40   5.30   0.90   0.30   0.90   1.30   0.0     6.60    0.0    0.0     0.60   0.0
 17   130.0    7315    7315$   9.00   0.50  57.80   6.20   2.30   0.0    0.80   0.0    0.80   0.0     4.40    0.0    0.0     7.50   4.10
 18   140.0    7501    7501$   5.10   0.20  64.30   8.50   4.10   0.70   0.70   2.40   0.50   0.0     4.40    0.0    0.0     2.70   0.0
 19   150.0    7686    7686$   1.60   0.50  68.50   6.50   3.30   1.20   1.60   1.60   1.60   0.0     4.00    0.0    0.0     3.00   0.0
 20   160.0    7871    7871$   1.50   0.80  69.10   2.90   2.10   0.20   0.60   1.30   2.10   0.0     4.80    0.20   0.0     5.50   0.20
 21   170.0    8057    8057$   2.50   0.50  75.40   2.50   1.60   0.20   0.50   1.10   2.70   0.0     3.20    0.0    0.0     4.10   0.0
 22   180.0    8242    8242$   1.00   1.00  74.30   2.20   1.00   0.0    0.60   0.40   2.40   0.0     4.50    0.0    0.0     3.50   0.40
 23   185.0    8335    8335$   4.20   2.50  73.90   3.20   0.20   0.0    1.20   2.10   1.40   0.0     4.10    0.0    0.0     1.10   0.0
 24   186.0    8353    8353$   7.10   0.40  71.50   6.30   0.0    0.0    0.0    0.80   1.30   0.0     0.40    0.0    0.0     2.10   0.40
*****************************************************************************************************************************************
POLLEN SUMS FROM LEVEL 1 TO  24:

   802      760      556      671      487      614      532      343      604      664      809      549      750      430      426      320
   389      412      428      524      439      510      567      239

*****************************************************************************************************************************************

LINEAR INTERPOLATION ON CHRON FILE NUMBER  2
   6    1                                                                      LINEAR INTERPOLATION ON CHRON FILE NUMBER  1
     000     5800     8300    10500    12750    17500                             5    1
     300     4600     5145     6545     7260     8150                                   0     8300    10500    12750    17500
     100      200      200      110      160      150                                 300     5145     6545     7260     8150
FARNHAM BOG, PQ:                                                                      100      200      110      160      150
4 C-14 DATES WITH 4.6K DATE FOR TSUGA DECLINE ADDED.                           FARNHAM BOG, PQ:
NO RAGWEED RISE, SURFACE PLOWED.  300YR DATE FOR                               4 C-14 DATES, NO RAGWEED RISE, 300 YR DATE SUGGESTED
TOP FROM P.RICHARD, OCT. 1980.                                                 BY P. RICHARD. SURFACE HAS BEEN PLOWED.  186 CM CORE.
```

sum for each pollen spectrum is listed, and the spectra with pollen sums of less than 75 grains were deleted. The low pollen counts in these spectra might yield spurious pollen percentages. The tables give the pollen values for all depths sampled in each core and also give the dates for each depth based on the chosen dating scheme. These tables show the pollen data as recorded at each core, and indicate the time interval between adjacent pollen samples. They also reveal the time span from the lowest pollen sample in each core to the top sample and thus aid the choice of the oldest and youngest dates at which data can be mapped at each site.

The oldest date mapped at each site was no more than 200 years older than the oldest radiocarbon date at the site (Table 1) or, for Princeville, the oldest pollen-stratigraphic date. Montagnais is an exception because the data for 9,000 yr B.P. are mapped when the oldest date is 8,510 yr B.P. The youngest date mapped in each core depends on the date interpolated for the topmost pollen sample. For example, an interpolated age of 3,000 yr B.P. at 55 cm in Princeville meant that no values were mapped for any date younger than 3,000 yr B.P. at this site.

Tables of the pollen percentages interpolated for each 500-year date from 500 yr B.P. to 10,000 yr B.P. were produced next. These list the pollen percentages that were mapped for each site. At each site, the value at each 500-year date was linearly interpolated from the values at the two samples bounding this date (e.g., for 6,000 yr B.P. at Farnham, the values for 5,590 and 6,226 yr B.P. were used (Table 2)). Next, computer files were created to allow mapping of the data. These files organize the data by date and by pollen type and include data from all sites with interpolated values at a given date. Computer files listing the differences or changes in the pollen values from one time interval to the next were also produced.

The Maps: Choice of Contours

Maps of pollen percentages were then printed for the major pollen types at selected dates during the Holocene. The values for some types were summed in order to make it easier to contour the patterns for these types. Maps are presented for the sum of *Salix, Artemisia,* the Gramineae pollen and the sum of *Ulmus* and *Fraxinus* pollen. The dates mapped were 0, 500, 2,000, 4,000, 5,000, 6,000, 8,000, 9,000, and 10,000 yr B.P.

A map for 7,000 yr B.P. was also produced for *Tsuga* pollen because *Tsuga* trees first arrived in southern Québec about that time.

An isopoll map was drawn for the pollen values of each type at each date. These maps indicated that isochrones for selected isopolls could illustrate the major trends for each of the major pollen types. Most of these isopolls were chosen to outline the areas in which the taxon was either abundant within the vegetation or, at least, a significant component on the landscape. A few of the isopolls (e.g., 3% *Alnus*, 3% *Quercus*, and 3% *Ulmus* and *Fraxinus* pollen) were chosen to indicate changes near or beyond the range for certain taxa. We followed the philosophy of Webb *et al.* (1983) in mapping the pollen data directly rather than mapping interpreted vegetational features (e.g., plant communities or range boundaries (Davis 1981A)). We then described in narrative form the changes in the vegetation as indicated by the patterns that emerge on the pollen maps. The pollen data are proxies for direct measurements of the vegetation, and careful choice of the isopolls mapped permitted descriptions of the changing location and composition of treeless vegetation, aspen woodland, taïga, boreal forest, and mixed forest.

For certain of the genera (*Picea, Abies, Pinus, Betula, Tsuga, Acer, Ulmus, Fraxinus,* and *Quercus)*, the empirical relationships between pollen and tree percentages influenced the choice of which isopoll to map. Webb *et al.* (1981) showed that the pollen percentages for *Pinus, Betula,* and *Tsuga* are higher than their tree percentages, those for *Ulmus* and *Picea* were less than their tree percentages, and those for *Abies, Fraxinus,* and *Acer* were much less than their tree percentages. Within forested landscapes, significant quantities of both *Pinus* and *Quercus* pollen are transported beyond 30 km, and up to 15% *Pinus* pollen and 6% *Quercus* pollen can be blown in from beyond this distance. Certain of these distortions are even more pronounced before the afforestation phase at any site (Richard 1977).

The contours for several pollen types were used to illustrate the regions that initially had treeless vegetation. These included the 10% isopoll for Cyperaceae and the 15% isopoll for the sum of *Salix, Artemisia,* and Gramineae. The 5% isopoll for this sum was used to indicate open woodland vegetation. The 3% isopoll for *Populus* pollen outlined areas with significant numbers of *Populus* trees, and the 10% isopoll indicated regions dominated by aspen woodlands. The regions with shrub-dominated open vegetation were also sum for each pollen spectrum is listed, and the spectra with pollen sums of less than 75 grains were deleted. The low pollen counts in these spectra might yield spurious pollen percentages. The tables give the pollen values for all depths sampled in each core and also give the dates for each depth based on the chosen dating scheme. These tables show the pollen data as recorded at each core, and indicate the time interval between adjacent pollen samples. They also reveal the time span from the lowest pollen sample in each core to the top sample and thus aid the choice of the oldest and youngest dates at which data can be mapped at each site.

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A map for 7,000 yr B.P. was also produced for *Tsuga* pollen because *Tsuga* trees first arrived in southern Québec about that time.

An isopoll map was drawn for the pollen values of each type at each date. These maps indicated that isochrones for selected isopolls could illustrate the major trends for each of the major pollen types. Most of these isopolls were chosen to outline the areas in which the taxon was either abundant within the vegetation or, at least, a significant component on the landscape. A few of the isopolls (e.g., 3% *Alnus*, 3% *Quercus*, and 3% *Ulmus* and *Fraxinus* pollen) were chosen to indicate changes near or beyond the range for certain taxa. We followed the philosophy of Webb *et al.* (1983) in mapping the pollen data directly rather than mapping interpreted vegetational features (e.g., plant communities or range boundaries (Davis 1981A)). We then described in narrative form the changes in the vegetation as indicated by the patterns that emerge on the pollen maps. The pollen data are proxies for direct measurements of the vegetation, and careful choice of the isopolls mapped permitted descriptions of the changing location and composition of treeless vegetation, aspen woodland, taïga, boreal forest, and mixed forest.

For certain of the genera *(Picea, Abies, Pinus, Betula, Tsuga, Acer, Ulmus, Fraxinus,* and *Quercus),* the empirical relationships between pollen and tree percentages influenced the choice of which isopoll to map. Webb *et al.* (1981) showed that the pollen percentages for *Pinus, Betula,* and *Tsuga* are higher than their tree percentages, those for *Ulmus* and *Picea* were less than their tree percentages, and those for *Abies, Fraxinus,* and *Acer* were much less than their tree percentages. Within forested landscapes, significant quantities of both *Pinus* and *Quercus* pollen are transported beyond 30 km, and up to 15% *Pinus* pollen and 6% *Quercus* pollen can be blown in from beyond this distance. Certain of these distortions are even more pronounced before the afforestation phase at any site (Richard 1977).

The contours for several pollen types were used to illustrate the regions that initially had treeless vegetation. These included the 10% isopoll for Cyperaceae and the 15% isopoll for the sum of *Salix, Artemisia,* and Gramineae. The 5% isopoll for this sum was used to indicate open woodland vegetation. The 3% isopoll for *Populus* pollen outlined areas with significant numbers of *Populus* trees, and the 10% isopoll indicated regions dominated by aspen woodlands. The regions with shrub-dominated open vegetation were also indicated by the 9% isopoll for *Alnus crispa* and the 30% isopoll for *Betula* pollen (in the northern part of its distribution during the early Holocene).

Conifer forest conditions similar to the present-day boreal forest were inferred from the maps by reference to the 3% isopoll for *Alnus*, the 5% isopoll for *Picea*, and the 3% isopoll for *Abies* pollen. The isochrones for 10% *Picea* pollen and 6% *Abies* pollen indicated the areas with abundant *Picea* and *Abies* trees (Richard 1976).

High values of *Pinus*, *Betula*, *Tsuga*, *Fagus*, and *Acer* pollen indicated a region dominated by mixed conifer-hardwood forest, with sugar-maple-dominated stands on the mesic sites. Significant numbers of *Pinus* trees were mapped by the 30% isopoll for *Pinus* pollen, and the 20% isopoll for *Pinus strobus* outlined the area in which this species dominated the *Pinus* populations. Both the 30% and 40% isopolls were used in mapping areas with significant numbers of *Betula* trees and shrubs. Inferences about which species of *Betula* produced the pollen depended upon which pollen types either co-occurred at the sites with high values of *Betula* pollen or were dominant at sites to the north or south of the *Betula* peaks. For instance, *Betula* shrubs were the most likely source of high values of *Betula* pollen when they occurred either in association with *Alnus* and Cyperaceae pollen or in areas north of the peak values of *Picea* and *Abies* pollen. At some sites (e.g., Ange), this has been confirmed by the presence of macrofossils of *B. glandulosa* (Labelle and Richard 1981). *Betula papyrifera* trees probably produced most of the *Betula* pollen in areas between the peak values of *Picea* and *Pinus* pollen, and *Betula lutea* trees were the main source of *Betula* pollen during the mid- to late-Holocene in areas where it, *Tsuga*, *Fagus*, and *Acer* pollen increased at the expense of *Pinus strobus* pollen.

Isopolls for 5% *Tsuga*, 3% *Fagus*, and 3% *Ulmus*-plus-*Fraxinus* pollen were used to indicate areas where these trees were present within the forests. The isopolls for 15% *Tsuga* pollen, 6% *Fagus* pollen, 3% *Acer* pollen, and 6% *Ulmus*-plus-*Fraxinus* pollen indicated the areas with abundant to significant numbers of these trees. Isochrones for 9% *Fagus* and 9% *Ulmus*-plus-*Fraxinus* pollen were also plotted in order to support the inferences drawn from the 6% isopolls.

Quercus pollen was mapped as an indicator of deciduous forest elements within southern Québec, but only the 3%, 6%, and 9% contours could be mapped because *Quercus* was never abundant in southern Québec. The 6% isopoll showed the areas in which *Quercus* trees were probably present (Webb *et al.* 1981), and the 9% isopoll indicated where these trees were most abundant. The 3% isopoll was of interest because it indicated long-distance transport of *Quercus* pollen during the period before 6,000 yr B.P. Some pollen from *Carya, Juglans,* and other trees of the deciduous forest was also present but in too small quantities for mapping. For instance, no sample contains more than 1.7% *Carya* pollen, and only Tortue and Atocas record 1% *Carya* pollen at one of the mapped dates (4,000 yr B.P.). These sites lie in the warmest part of Québec.

RESULTS

Cyperaceae, Gramineae, *Salix*, and *Artemisia*

The maps for Cyperaceae, Gramineae, and *Salix*-plus-*Artemisia*-plus-Gramineae pollen show that both treeless vegetation and open woodlands grew to the north of the Champlain Sea at 10,000 yr B.P. (Figures 3, 15). The maps for *Populus, Juniperus/Thuja, Alnus, A. crispa, Betula,* and *Picea* pollen show that trees and shrubs from these taxa grew among the herbs and *Salix* shrubs (Figures 3-5, 9). The open woodland and treeless vegetation then shrank rapidly in size within the study area until high values of Cyperaceae pollen were confined to three sites in the Laurentides at 6,000 yr B.P. After this time, high values of Cyperaceae, *Populus, Alnus crispa* and the sum of *Salix, Artemisia,* and Gramineae pollen occur at none of the sites studied, and forest grew throughout the study area. The isochrones for 10% Cyperaceae pollen and 15% *Salix*-plus-*Artemisia*-plus-Gramineae (Figure 3) show that treeless vegetation grew north of Montréal at 10,000 yr B.P., near Gabriel at 9,000 yr B.P., and near two sites along the southern face of the Laurentides at 8,000 yr B.P.

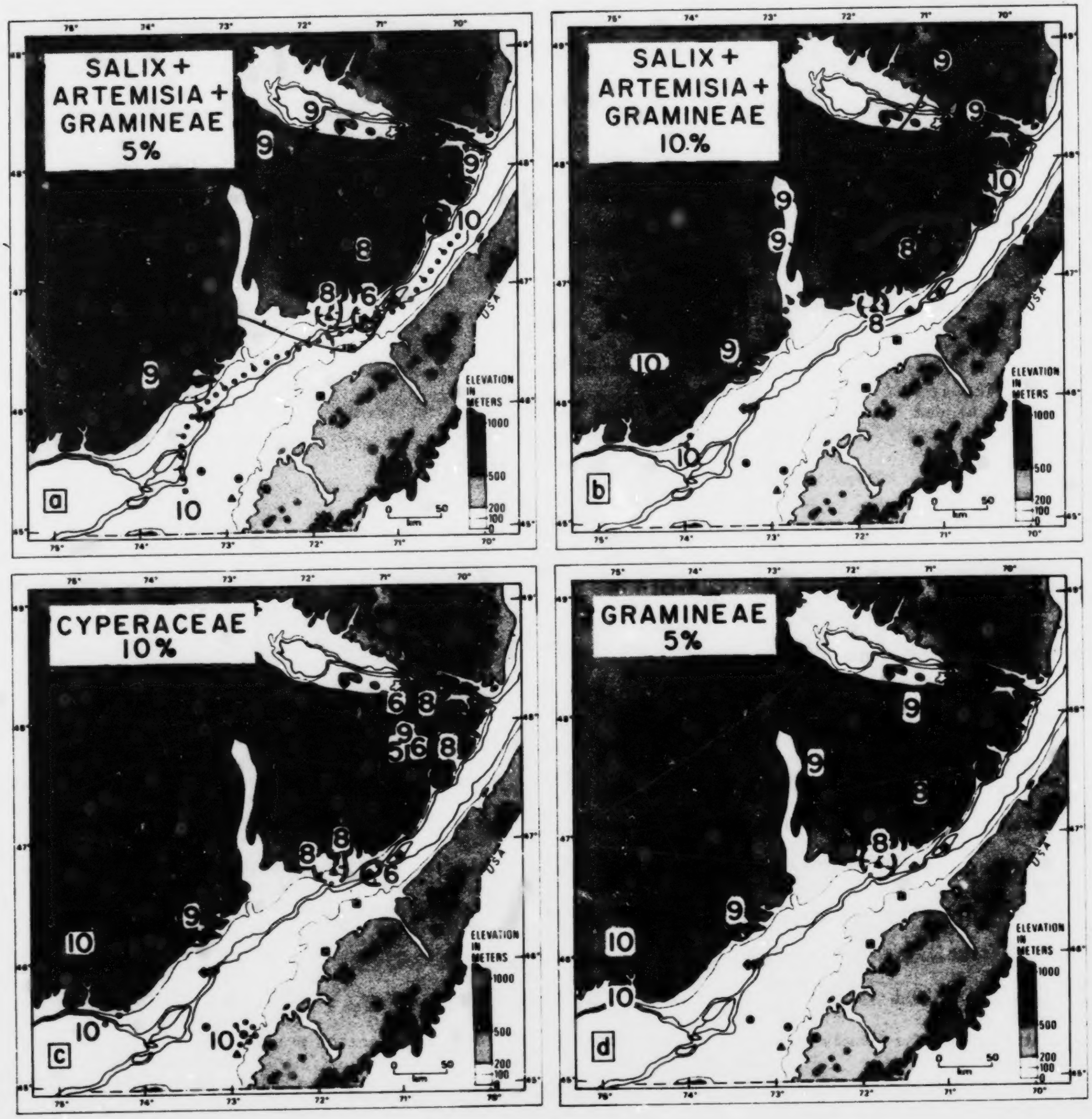

SALIX + ARTEMISIA + GRAMINEAE 5%
SALIX + ARTEMISIA + GRAMINEAE 10%
CYPERACEAE 10%
GRAMINEAE 5%
a
b
c
d
ELEVATION IN METERS
1000
500
200
100
0
0
50
km
USA
75°
74°
73°
72°
71°
70°
45°
46°
47°
48°
49°
6
8
9
10

FIGURE 3: *Isochrone maps with contours in* 10^3 *years for (a) 5% and (b) 10%* Salix-*plus-*Artemisia-*plus-Gramineae (willow, sage, and grass), (c) 10% Cyperaceae (sedge), and (d) 5% Gramineae pollen. The ticks along the isochrones point in the direction of increasing percentages for each pollen type.*

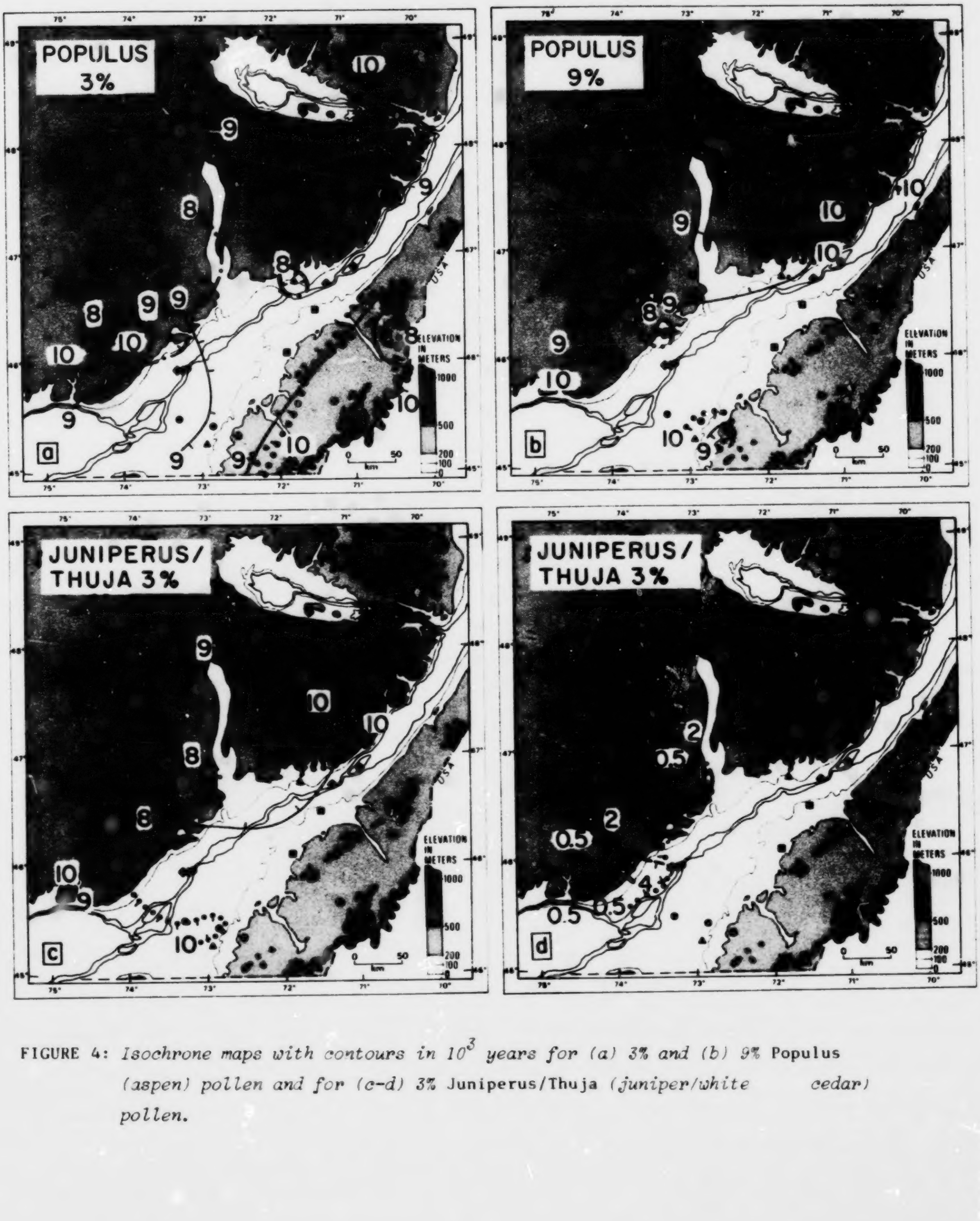

POPULUS 3%
POPULUS 9%
JUNIPERUS/ THUJA 3%
JUNIPERUS/ THUJA 3%
a
b
c
d
ELEVATION IN METERS
1000
500
200
100
0
0 50 km
USA
75°
74°
73°
72°
71°
70°
45°
46°
47°
48°
49°

FIGURE 4: *Isochrone maps with contours in* 10^3 *years for (a) 3% and (b) 9%* Populus *(aspen) pollen and for (c–d) 3%* Juniperus/Thuja *(juniper/white cedar) pollen.*

Populus

Populus woodlands followed a trend similar to that indicated for treeless vegetation (Figures 3, 4). Most of the sites had at least 3% *Populus* pollen at 10,000 and 9,000 yr B.P., but by 8,000 yr B.P. evidence for *Populus* trees exists at just three sites north of Montréal and one site in the valley near Québec City (Figure 4). *Picea* trees were growing near certain of the sites with high values of *Populus* pollen at 9,000 yr B.P., but *Pinus* trees had replaced the *Picea* trees by 8,000 yr B.P. At 10,000 yr B.P., *Populus* woodland grew in a mosaic of open forest and treeless vegetation, but by 9,000 yr B.P. *Populus* trees grew in open woodlands, in *Picea*-dominated forests, and in forests with *Pinus* trees. By 6,000 yr B.P., *Populus* pollen had ceased to make up more than 3% of the preserved pollen at any site (Figure 4).

Juniperus/Thuja

Most of the *Juniperus/Thuja* pollen probably came from *Juniperus* shrubs before 6,000 yr B.P. (Figure 4), when its main areas of abundance coincided with areas with abundant *Populus* and herbaceous pollen (Figures 3, 4). This pollen type never had values higher than 14% on any of the maps, and was most abundant and widespread at 9,000 yr B.P. when four sites had values above 9%. After a gap between 8,000 and 5,000 yr B.P., pollen values above 3% again appear north of Montréal and may record an increase in *Juniperus/Thuja* populations as *Alnus* and *Picea* populations were increasing in this area.

Alnus

Alnus plants grew throughout much of the region at 10,000 yr B.P., and *A. crispa* was the main type represented to the north and south of the Champlain Sea (Figures 5, 16). High values of *A. crispa* (above 9%) pollen appear first at 9,000 yr B.P. and continue widespread in the northeast until 8,000 yr B.P. (Figure 5). These high values indicate growth of shrub-dominated vegetation or open woodlands in this area. After this time, most high values appear at isolated individual sites and probably reflect only local conditions near these sites. The maps for 3% *Alnus* pollen show that *Alnus*

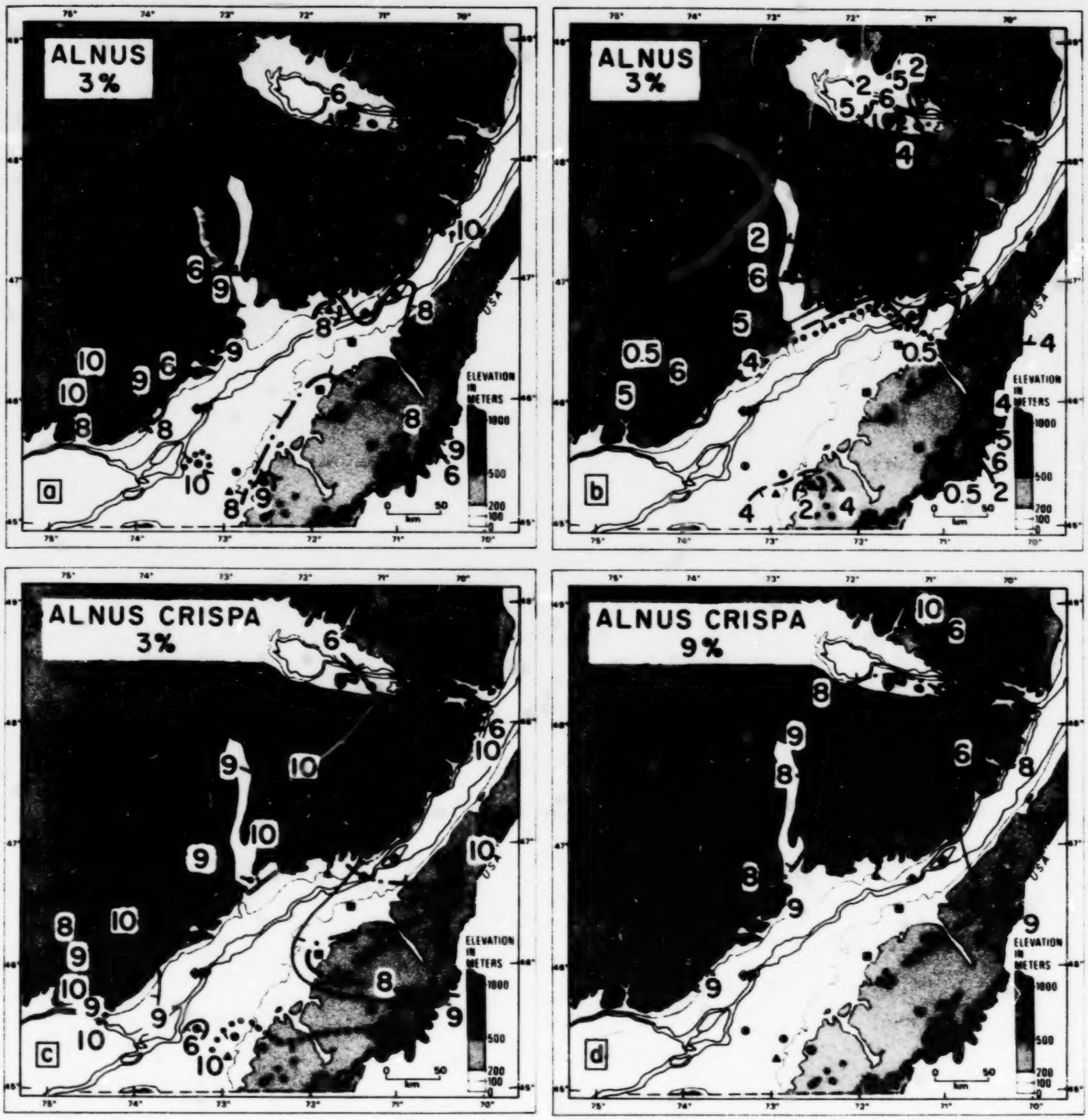

ALNUS 3%
a
ALNUS 3%
b
ALNUS CRISPA 3%
c
ALNUS CRISPA 9%
d
ELEVATION IN METERS
1000
500
200
100
0
0 50
km
USA
75°
74°
73°
72°
71°
70°

FIGURE 5: *Isochrone maps with contours in* 10^3 *years for (a-b) 3%* Alnus *(alder) pollen and for (c) 3%, and (d) 9%* Alnus crispa *(green alder) pollen.*

populations were widespread until after 8,000 yr B.P., following which they moved northward and became a common component of the regional vegetation in only the Laurentides and the Eastern Highlands. The populations within the 3% contour moved little after 6,000 yr B.P. except to extend southward between 2,000 and 500 yr B.P. into the region just north of Montréal. *Alnus rugosa* plants dominated the *Alnus* populations after 6,000 yr B.P. because no sites had more than 3% *A. crispa* pollen after this date.

Picea and Abies

The isochrone maps for *Picea* and *Abies* pollen show that their tree populations moved northward from 10,000 to 5,000 yr B.P. and then back southward, particularly after 4,000 yr B.P. (Figures 6, 7). During the Holocene, these two genera parallel each other in their changing abundance patterns. In the mid-Holocene, the Laurentides north of Québec City were one centre for *Picea-Abies* forests. Since then the populations for these trees have expanded south of the St. Lawrence River mainly at high elevations, and the 5% contour for *Picea* pollen has moved southwestward almost to Montréal. The isochrones for these two types along with the 3% contour for *Alnus* pollen (Figure 5) provide the best record for the changing position and composition of the conifer-dominated forests in southern Québec. Their association with Cyperaceae pollen in the Laurentides before 5,000 yr B.P. indicates that taïga vegetation was more extensive in these highlands during the early Holocene than today (Figures 3, 6, 7). Macrofossils of *Picea mariana, P. glauca,* and *Abies balsamea* were present at Ange in the northeastern Laurentides by 9,500 yr B.P. (Labelle and Richard 1981).

Pinus

At 10,000 yr B.P., *Pinus* values exceeded 30% at only one site, Mauricie, which is north of the Champlain Sea (Figure 8). This high value probably resulted from long distance transport of *Pinus* pollen into the open landscape there. Elsewhere few *Pinus* trees grew in southern Québec until their immigration from the south between 10,000 and 9,000 yr B.P. *Pinus divaricata*-type pollen dominated the counts of *Pinus* pollen at 10,000 yr B.P., but appreciable numbers of *Pinus strobus* grains were present by 9,000 yr B.P., and trees of this species dominated the *Pinus* populations from then on

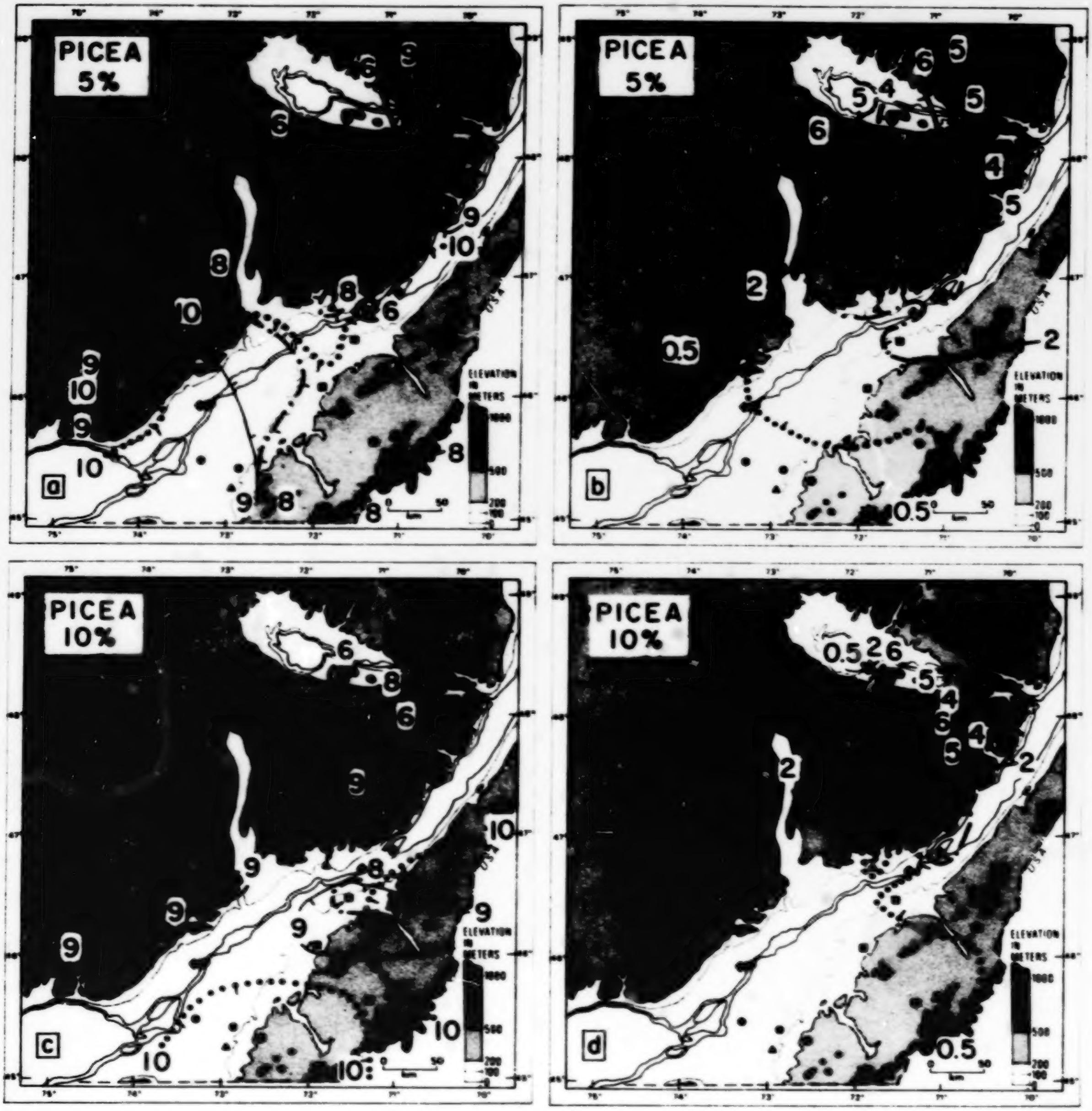

PICEA 5%
PICEA 5%
PICEA 10%
PICEA 10%
a
b
c
d
U.S.A.
ELEVATION IN METERS
1000
500
200
100
0
0 km 50
75°
74°
73°
72°
71°
70°

FIGURE 6: *Isochrone maps with contours in* 10^3 *years for (a-b) 5% and (c-d) 10%* Picea *(spruce) pollen.*

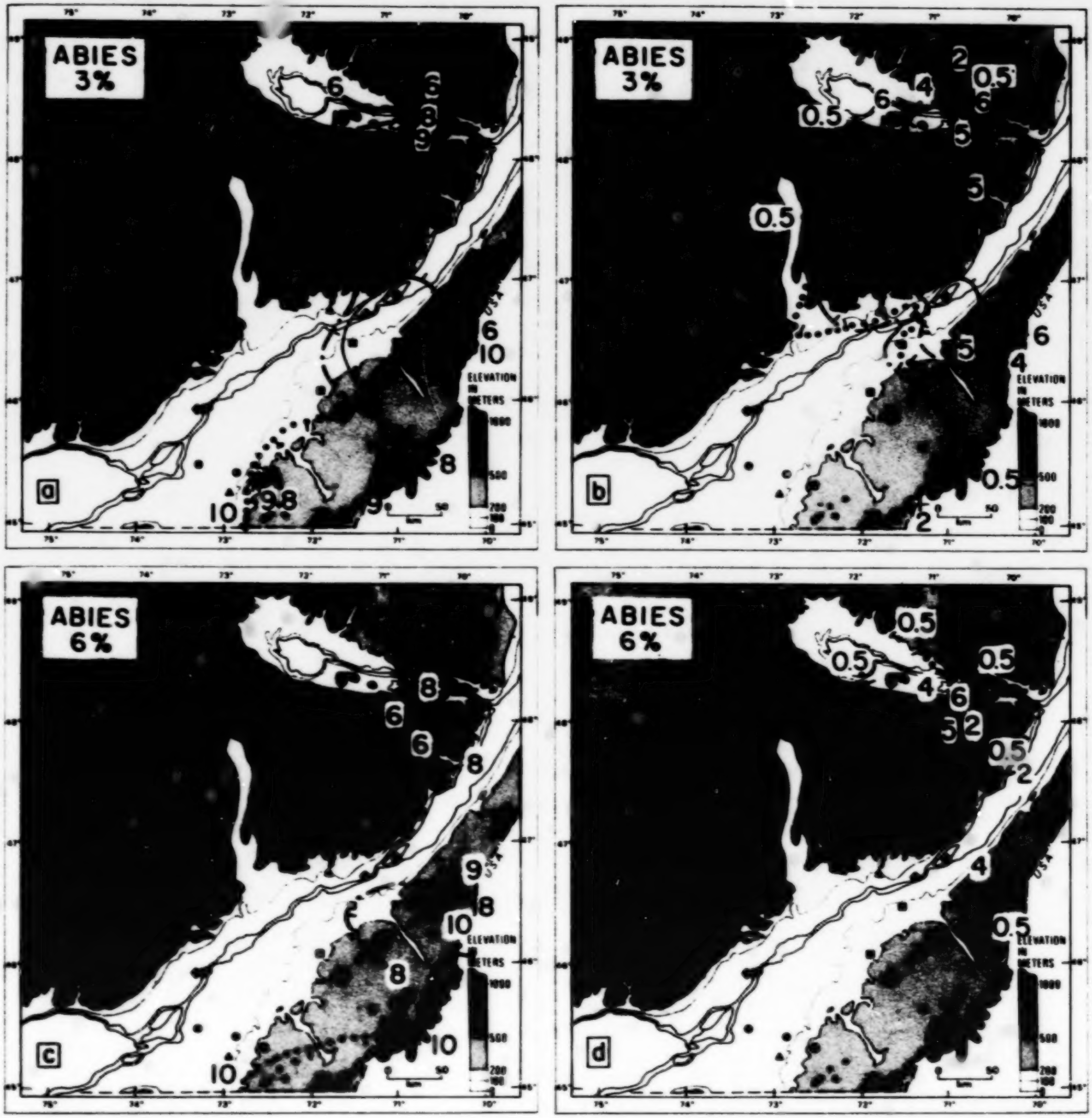

ABIES 3%
ABIES 3%
ABIES 6%
ABIES 6%
a
b
c
d
75°
74°
73°
72°
71°
70°
ELEVATION IN METERS
1000
500
200
100
0
km
0
50
USA
6
8
9
10
9.8
0.5
2
4
5

FIGURE 7: *Isochrone maps with contours in 10^3 years for (a-b) 3% and (c-d) 6%* Abies *(fir) pollen.*

(Figure 7). At 8,000 yr B.P., forests with many *Pinus* trees were more widespread and abundant than at any other time during the Holocene.

The region in which *Pinus* trees were most numerous shifted northward between 8,000 and 6,000 yr B.P. and became confined to a narrow belt in the centre of the study region. *Tsuga* and *Betula* (probably *B. lutea*) populations displaced the *Pinus strobus* trees in the south (Figures 9, 10), while the *Pinus* population displaced *Betula* (probably *B. papyrifera*), *Alnus*, *Picea*, and *Abies* populations to the north (Figures 5, 6, 7, 9). After 6,000 yr B.P., the population centre for *Pinus strobus* shifted westward and the area of most numerous *Pinus* trees shrank. Figure 7 shows high values of *Pinus* pollen at only two sites by 500 yr B.P. The peak for the distribution and abundance of forests rich in *Pinus* pollen thus was from 9,000 to 4,000 yr B.P.

Betula

At 10,000 yr B.P., large populations of *Betula* shrubs grew in the tundra and woodlands of the Laurentides, and significant populations of *Betula* trees (probably *B. papyrifera*) grew in the highlands in the southeast (Figures 9, 10). By 9,000 yr B.P., the shrub populations had contracted in the north while the tree population had expanded in the south, and macrofossils of *B. papyrifera* were present at Ange northeast of Québec City (Labelle and Richard 1981). With the expansion of *Pinus* populations in the south at 8,000 yr B.P. (Figure 8), the region with the highest numbers of *Betula* trees and shrubs became confined to a narrow band in the north-central area and in the southern Laurentides in the east. After 8,000 yr B.P., *Betula* populations expanded (particularly at moderate elevations) to the north and south of the St. Lawrence River Valley. This expansion most likely involved the appearance and increase of *B. lutea* populations in the south. From this time onwards, *Betula* is regionally the most ubiquitous and numerous pollen type.

With the decline in *Tsuga* populations after 5,000 yr B.P. (Figure 10), *Betula* populations expanded within the St. Lawrence River Valley, and at 4,000 yr B.P. all but two sites accumulated more than 30% *Betula* pollen. After 4,000 yr B.P. the isochrones for 40% *Betula* pollen indicate a decrease in *Betula* populations

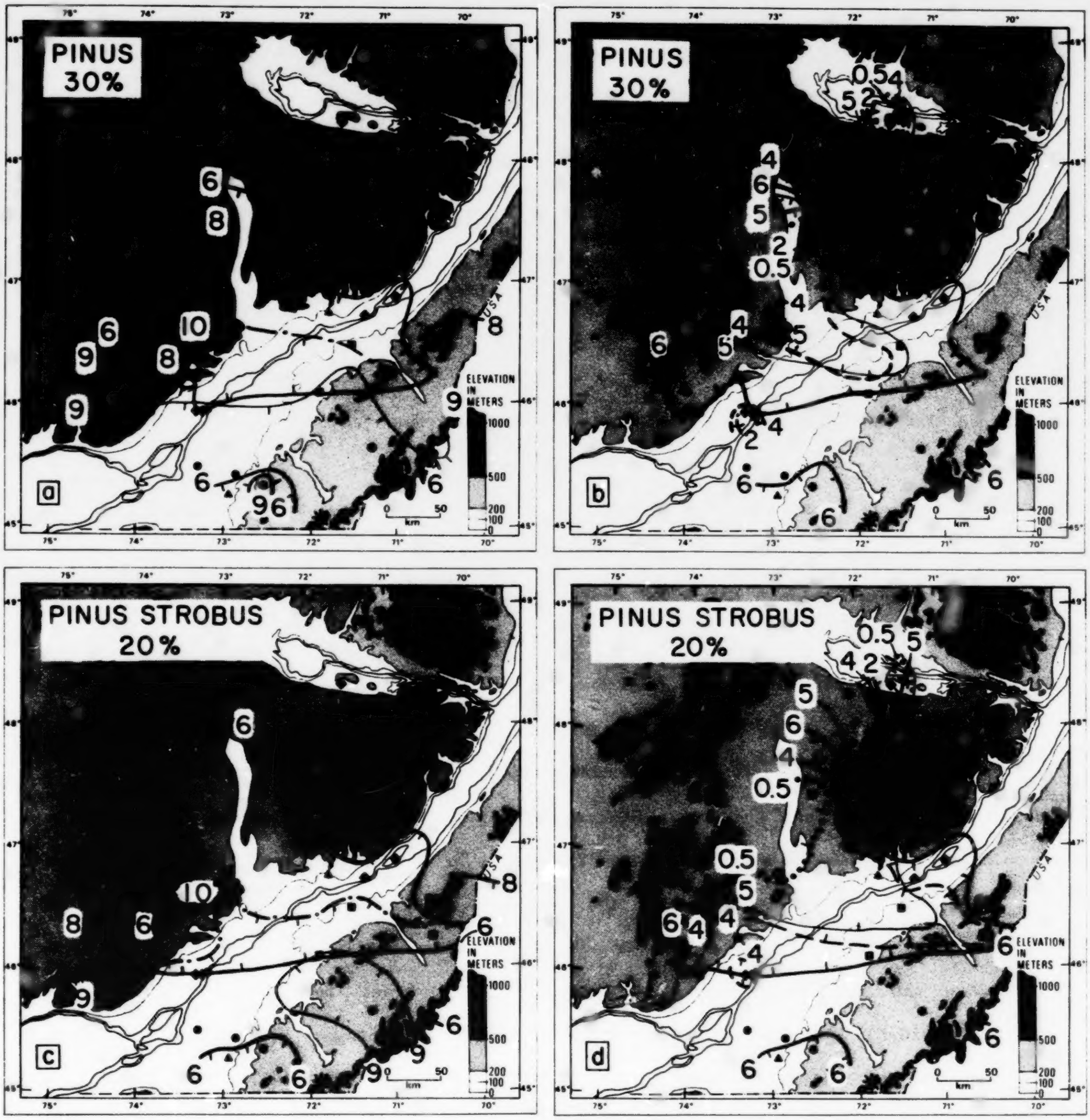

PINUS
30%
PINUS STROBUS
20%
a
b
c
d
ELEVATION IN METERS
1000
500
200
100
0
0
50
km
USA
75°
74°
73°
72°
71°
70°
45°
46°
47°
48°
49°

FIGURE 8: *Isochrone maps with contours in* 10^3 *years for (a-b) 30%* Pinus *(pine) pollen and for (c-d) 20%* Pinus strobus *(white pine) pollen.*

within the valley sites, but the isochrones for 30% *Betula* pollen indicate little change. *Betula* trees at moderate abundances were widespread, but forests with high values of *Betula* trees became less extensive especially in the St. Lawrence Valley and in the Laurentides.

Tsuga, Fagus, and *Acer*

The populations of these genera expanded only after 7,000 yr B.P. and grew mainly within the St. Lawrence River Valley (Figures 10, 11). Among these three genera, *Acer* trees were the first to grow in southern Québec (Figure 11A), but the populations of *Acer* remained low until after the appearance of *Fagus* trees just prior to 6,000 yr B.P. (Figure 11B).

Tsuga trees arrived before *Fagus* and grew in moderate numbers throughout the south as of 7,000 yr B.P. *Tsuga* populations expanded northward until 5,000 yr B.P. and then collapsed about 4,700 yr B.P., when the trees were probably attacked by a pathogen (Davis 1981B). By 2,000 yr B.P., the populations had again expanded, but their highest values were confined to the St. Lawrence River Valley. The isochrones for 5% *Tsuga* pollen show little change after 2,000 yr B.P., but the isochrone for 15% *Tsuga* pollen indicates that the forests with abundant *Tsuga* trees became less prevalent at the northeastern end of the St. Lawrence Valley, as *Picea, Abies,* and *Betula* populations increased in abundance there (Figures 6, 7, 10).

After their first appearance in the southwest by 6,000 yr B.P., *Fagus* populations expanded their range steadily northward within the valley until 2,000 yr B.P. After 2,000 yr B.P., the area with high abundances of *Fagus* trees in the forests decreased (Figures 11C,D). *Acer* populations paralleled the changes in *Fagus* populations, but expanded no farther northward after 4,000 yr B.P. (Figure 11A). Within the late Holocene, the area occupied by abundant populations of *Tsuga, Fagus,* and *Betula* decreased, but the areas of moderate to low populations of these trees changed relatively little.

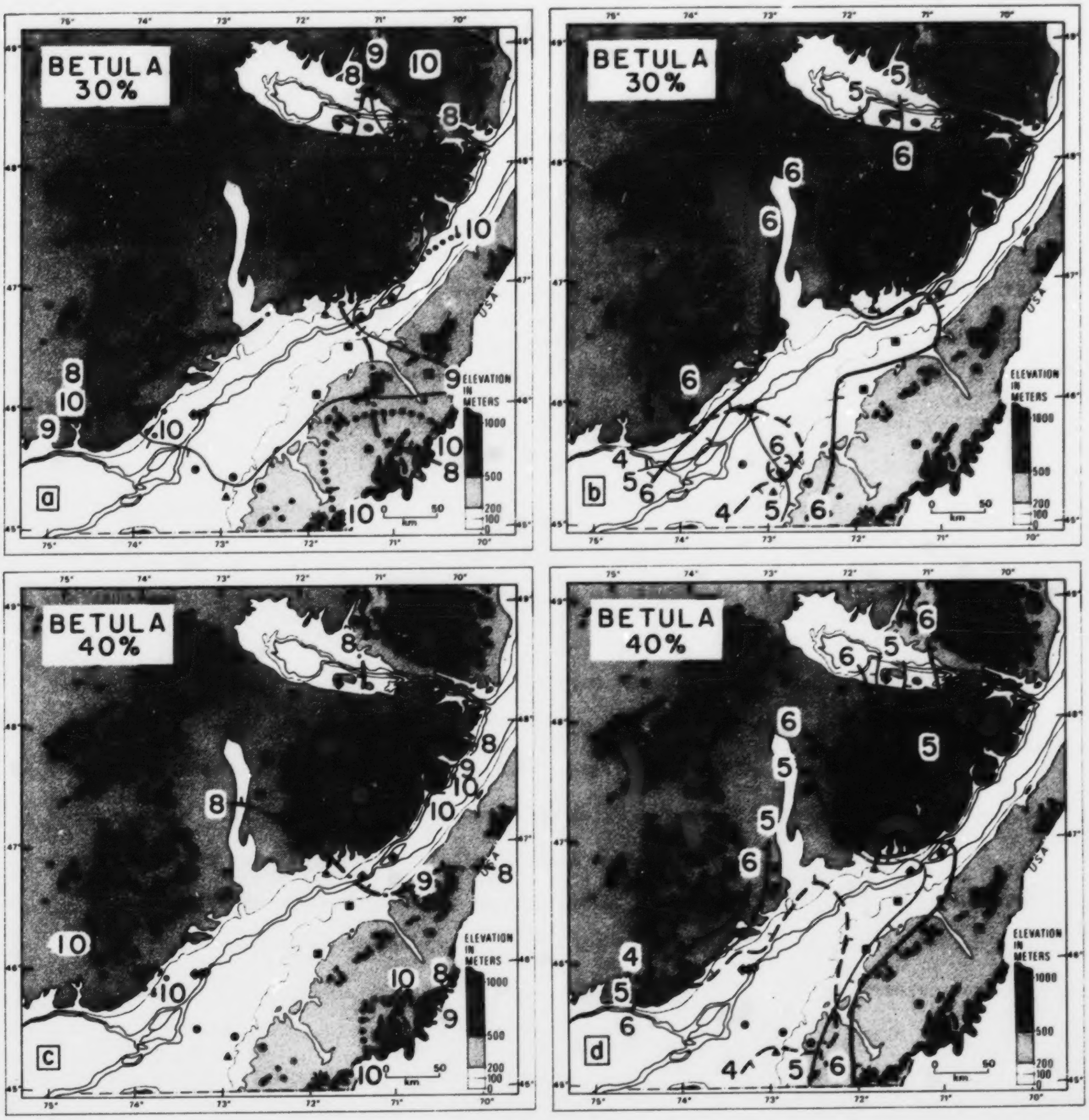

BETULA 30%
a
BETULA 30%
b
BETULA 40%
c
BETULA 40%
d
ELEVATION IN METERS
1000
500
200
100
0
0 50 km
USA
75° 74° 73° 72° 71° 70°
49° 48° 47° 46° 45°

FIGURE 9: *Isochrone maps with contours in* 10^3 *years for (a-b) 30% and (c-d) 40% of* Betula *(birch) pollen.*

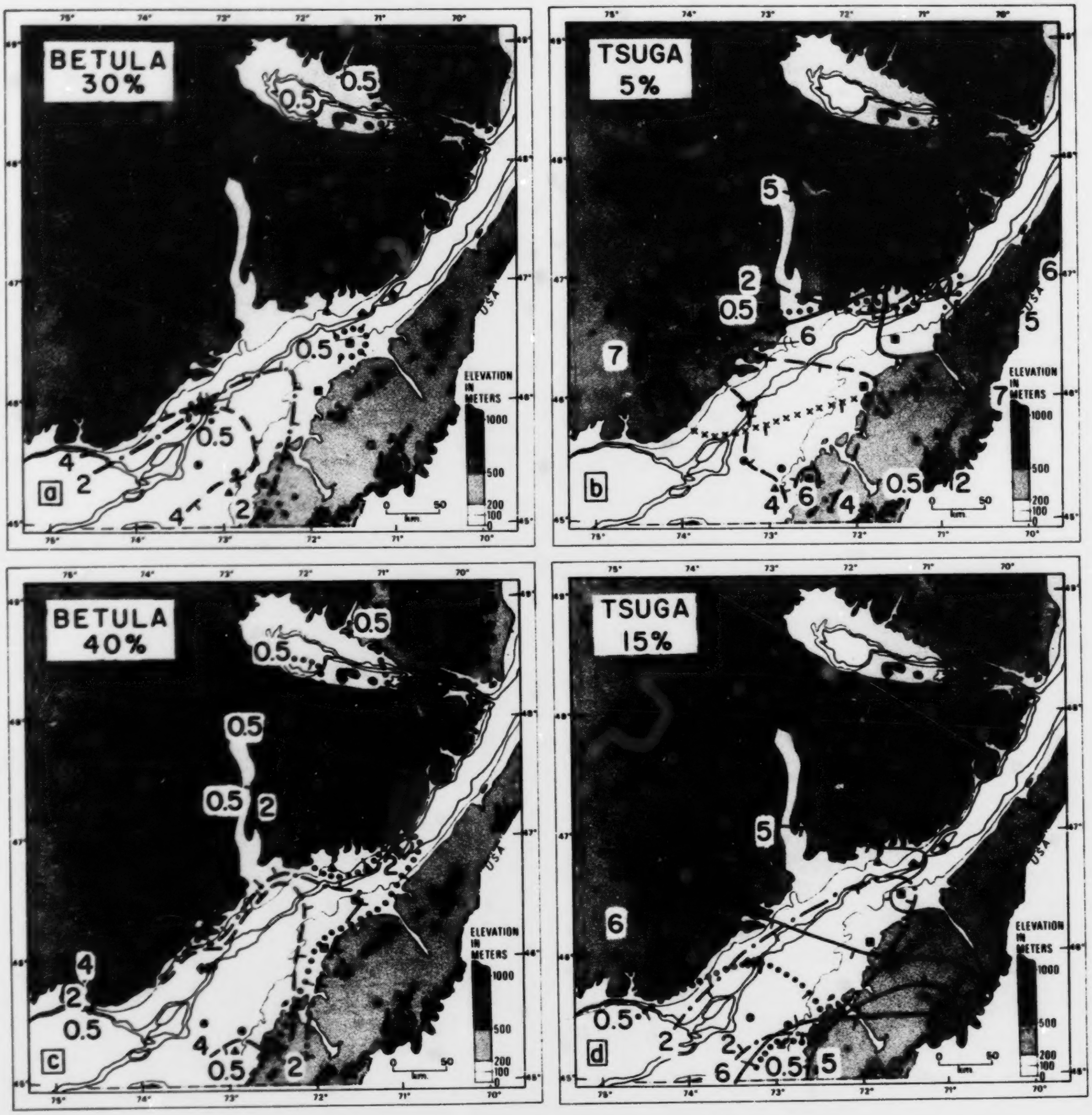
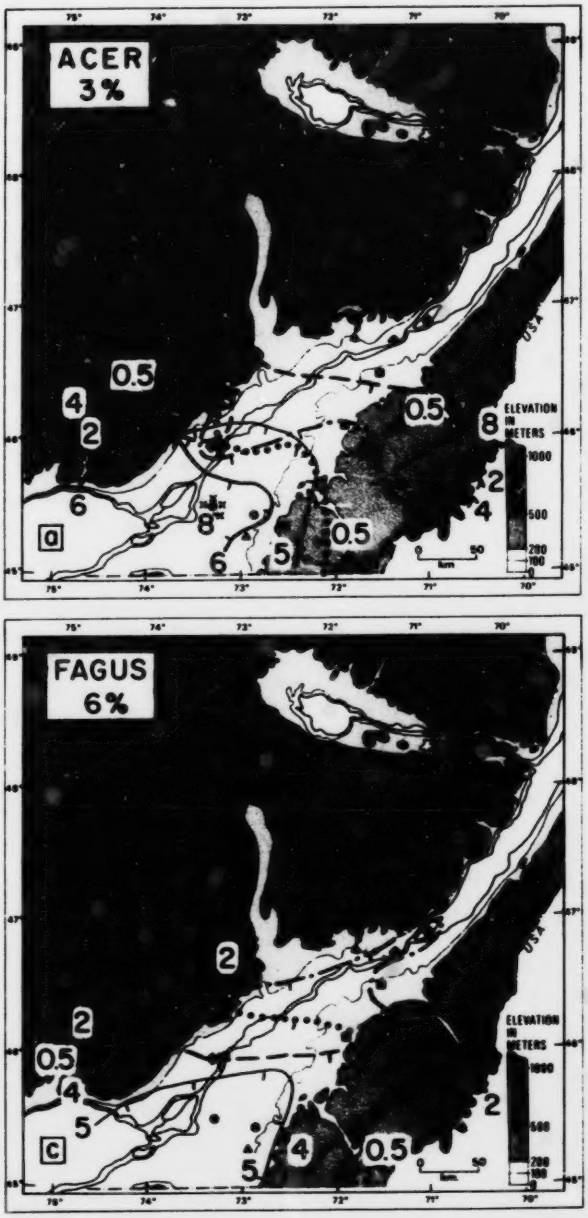

BETULA 30%
TSUGA 5%
BETULA 40%
TSUGA 15%
a
b
c
d
ELEVATION IN METERS
1000
500
200
100
0
USA
0
50
km
75°
74°
73°
72°
71°
70°
45°
46°
47°
48°
49°
0.5
2
4
5
6
7

FIGURE 10: *Isochrone maps with contours in 10^3 years for (a) 30% and (c) 40%* Betula *(birch) pollen and for (b) 5% and (d) 15%* Tsuga *(hemlock) pollen.*



ACER 3%
FAGUS 3%
FAGUS 6%
FAGUS 9%
a
b
c
d
0.5
2
4
5
6
8
USA
ELEVATION IN METERS
1000
500
200
100
0
0
50
km
75°
74°
73°
72°
71°
70°

FIGURE 11: *Isochrone maps with contours in* 10^3 *years for (a) 3%* Acer *(maple) pollen and for (b) 3%, (c) 6%, and (d) 9%* Fagus *(beech) pollen.*

Ulmus and *Fraxinus*

The isochrone for the 6% contour shows that the modest populations for *Ulmus* and *Fraxinus* were most numerous only within the southwestern part of the St. Lawrence River Valley (Figure 13). These populations expanded northeastward from 9,000 to 6,000 yr B.P., and then contracted steadily southwestward until 500 yr B.P. The general region in which *Ulmus* and *Fraxinus* trees grew is outlined by the isochrones for the 3% contour (Figure 12). This region expanded from 10,000 to 6,000 yr B.P., remained fixed until 4,000 yr B.P., and then contracted somewhat until 500 yr B.P. The trend in the *Ulmus* and *Fraxinus* populations parallels that for *Picea* and *Abies* populations in the east and northeast (Figures 6, 7, 12, 13). First the population of these deciduous forest trees expanded northeastward as the populations of conifer forest trees retreated in this direction, and then this trend reversed. As with *Tsuga, Fagus,* and *Betula,* the low-valued isopoll marking the range boundary moved much less during the late Holocene than the higher valued isopolls.

Quercus

From 6,000 to 500 yr B.P., the southwestward retreat of *Quercus* populations (Figure 14D) paralleled the general trend in abundance and range of several other deciduous taxa. Before 6,000 yr B.P., however, the isochrones for 6% *Quercus* pollen traced out a unique pattern (Figure 13C). *Quercus* pollen was most widespread at 9,000 yr B.P. and contracted southward until 6,000 yr B.P. This pattern may reflect a certain amount of long-distance transport of *Quercus* pollen into the treeless vegetation and open woodlands north of the St. Lawrence River Valley at 9,000 and 8,000 yr B.P. Plant macrofossil evidence, however, has shown that *Quercus* trees were early migrants into some areas (Mott *et al.* 1981).

The contours for 3% *Quercus* pollen show even more clearly the effects of long-distance transport (Figures 13A,B), because 6% is the average value for *Quercus* pollen (in forested terrain) when no trees grow near a site (Webb *et al.* 1981). At 9,000 yr B.P., 3% or more *Quercus* pollen occurred at most sites. The area with over 3% *Quercus* pollen then contracted steadily until 6,000 yr B.P., as forests developed north of the St. Lawrence Valley. At 4,000 yr B.P., only a modest population of *Quercus*

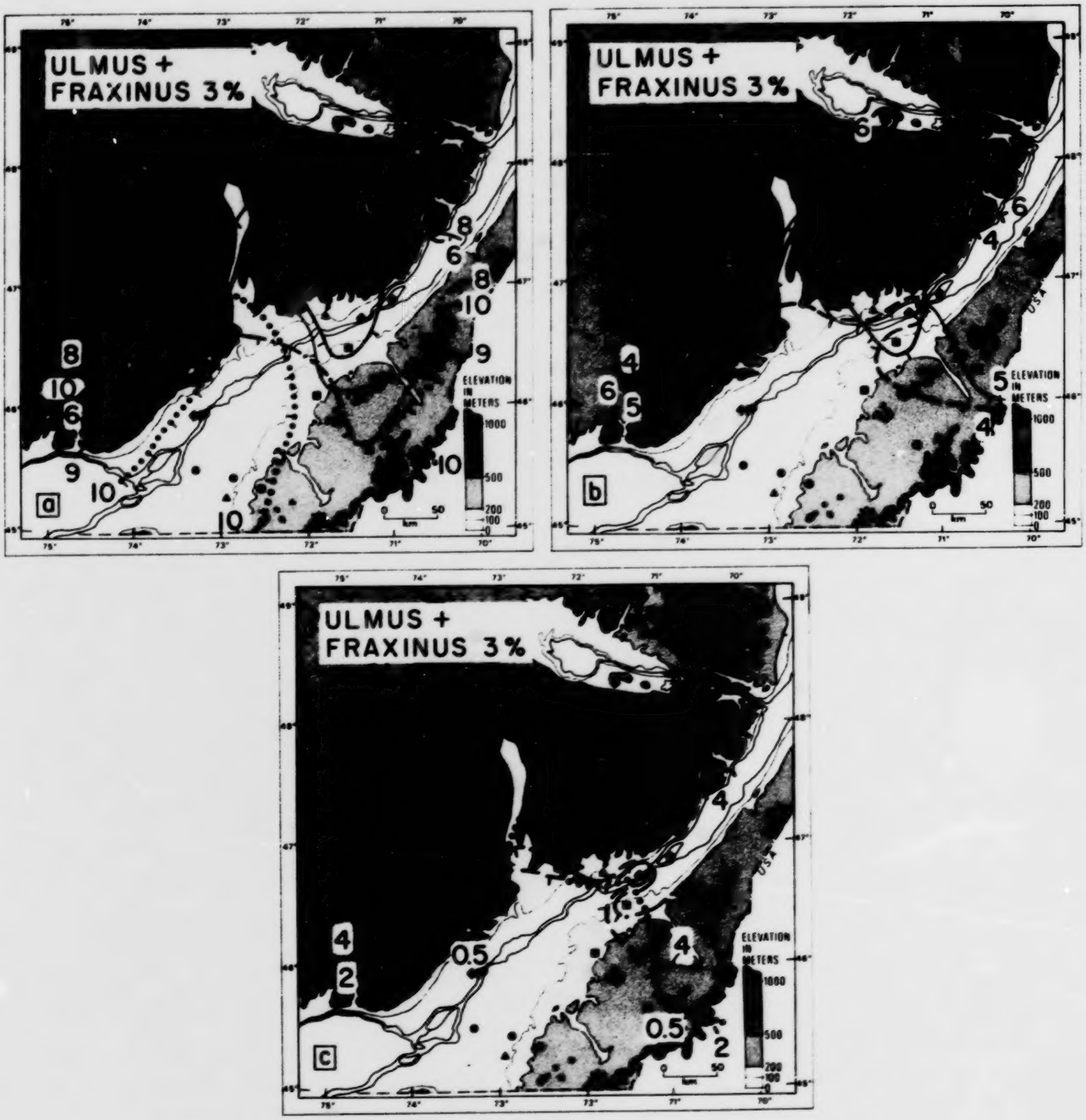

ULMUS + FRAXINUS 3%
a
b
c
8
10
6
9
10
10
8
6
8
10
9
10
6
4
6
4
6
5
5
4
4
2
0.5
1
4
0.5
2
ELEVATION IN METERS
1000
500
200
100
0
0
50
km
USA
75°
74°
73°
72°
71°
70°
45°
46°
47°
48°
49°

FIGURE 12: *Isochrone maps with contours in* 10^3 *years for (a-c) 3%* Ulmus-*plus*-Fraxinus *(elm and ash) pollen.*

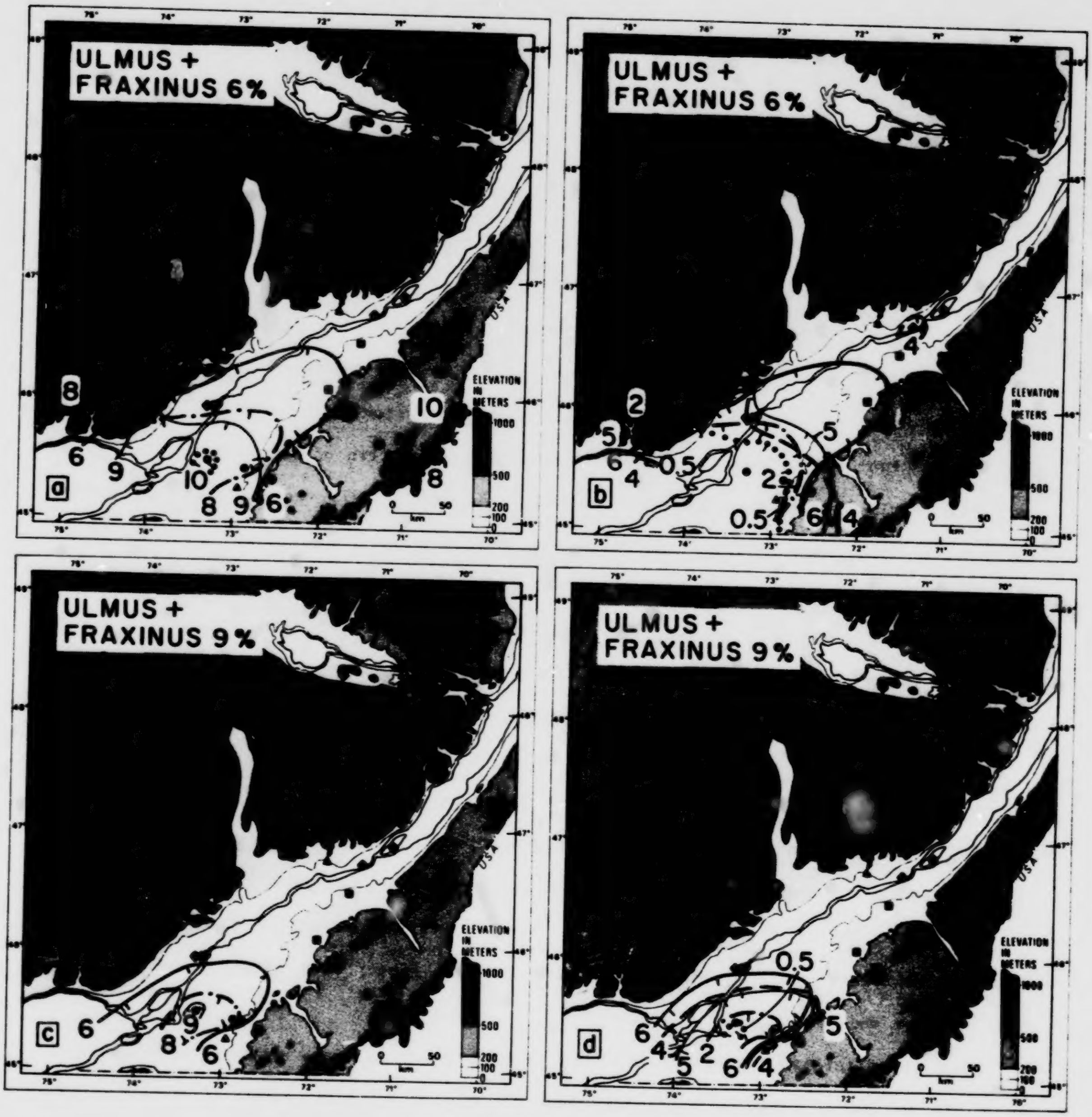

ULMUS + FRAXINUS 6%
a
8
10
6
9
10
8
9
6
8
ULMUS + FRAXINUS 6%
b
2
4
5
6
4
0.5
5
2
0.5
6
4
ULMUS + FRAXINUS 9%
c
6
9
8
6
ULMUS + FRAXINUS 9%
d
0.5
5
6
4
2
5
6
4
ELEVATION IN METERS
1000
500
200
100
0
km
0
50
75°
74°
73°
72°
71°
70°
49°
48°
47°
46°
45°
U.S.A.

FIGURE 13: *Isochrone maps with contours in* 10^3 *years for (a–b) 6% and (c–d) 9%* Ulmus *-plus-*Fraxinus *(elm and ash) pollen.*

trees was growing in southern Québec, and these trees were in the southeast (Figures 14, 15). This population decreased between 4,000 and 2,000 yr B.P. but then increased and expanded again by 500 yr B.P. (Figure 14).

Vegetational Changes through Time

Ten thousand years ago (Figure 16), the Laurentide ice-front was in the northernmost part of the area mapped and still covered the Lake St. John area (Prest 1969). A closed boreal forest of *Picea, Abies,* and *Betula* (probably *B. papyrifera*) grew in the Appalachian Highlands; a few *Quercus, Ulmus,* and *Fraxinus* trees grew along the shores of the Champlain Sea; and an open vegetation with a mosaic of *Populus* woodlands, shrub- and herb-dominated vegetation grew to the north of the Champlain Sea and on certain islands within the sea (Figure 16). Richard (1977) proposed that the early immigration and great initial abundance of *Populus* cf. *tremuloides,* on the north side of the Champlain Sea, was caused by a better adaptation of the seeds of this tree species to long-distance transport over the Champlain Sea, which was a palaeogeographic barrier. For a time, this barrier would have prevented other tree species from extending their populations to the north, leaving *Populus* almost alone in an otherwise treeless landscape (Mott 1978).

By 9,000 yr B.P., *Picea* and *Abies* forests with some *Pinus* trees were growing to the north of Lake Lampsilis in the west, and a mixture of open conifer forest, *Populus* woodlands, and shrub-dominated treeless vegetation grew near the other sites in the northeast (Figure 16). To the south, *Pinus* forests grew on the Monteregian Hills east of Montréal, and forests with *Pinus, Betula, Picea,* and *Abies* trees grew in the southeast and to the south of Québec City.

A mosaic of forests, woodlands, and open vegetation grew to the north of Lake Lampsilis at 8,000 yr B.P. *Populus* woodlands were in the west, just north of forests with abundant *Pinus strobus* trees. In the east, a mixture of forests, woodlands, and vegetation grew that was composed of *Alnus crispa, Betula, Salix* Cyperaceae, *Abies,* and *Picea* plants (Figure 17). Populations of *Picea* and *Abies*

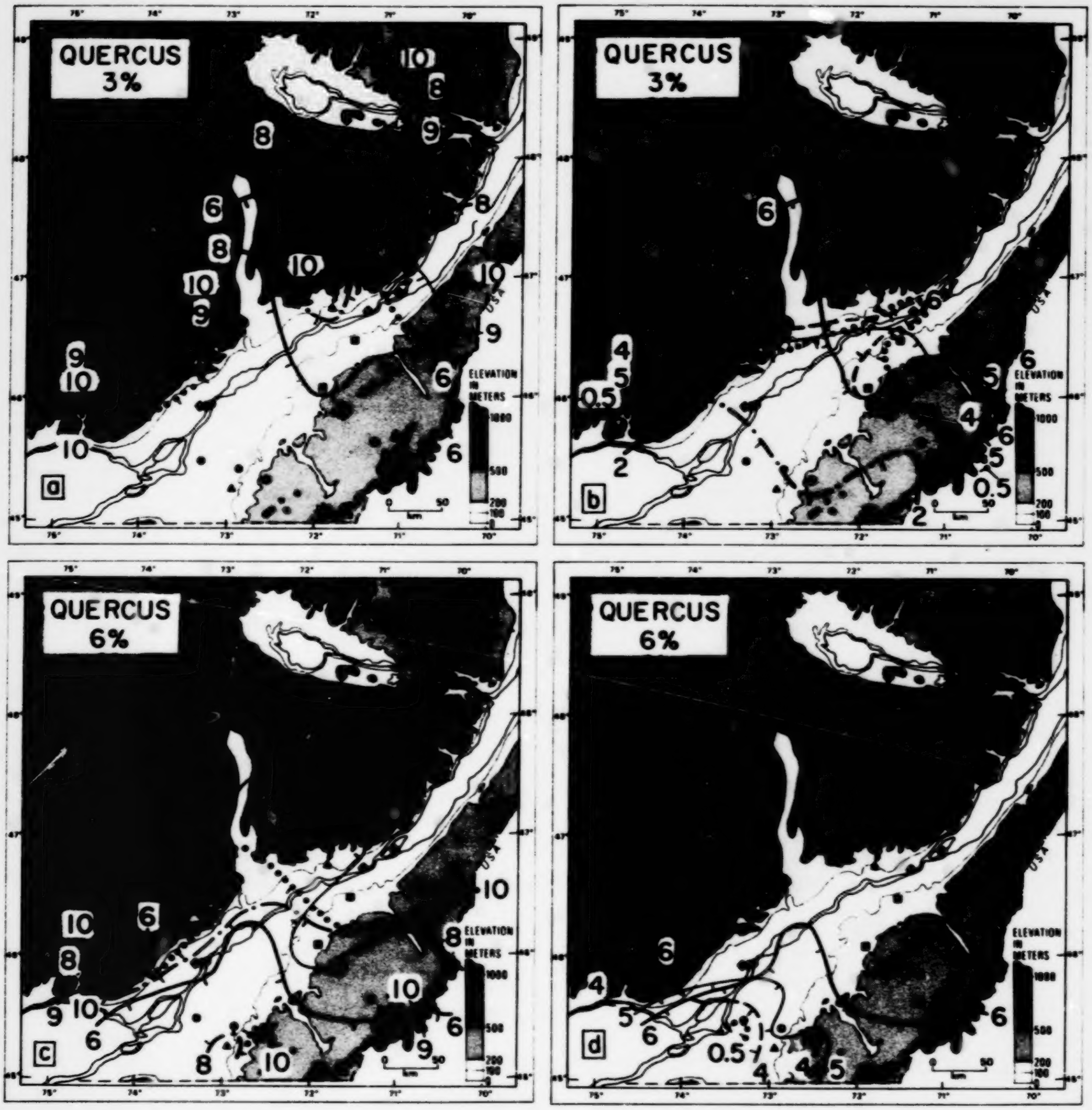

QUERCUS 3%
QUERCUS 3%
QUERCUS 6%
QUERCUS 6%
a
b
c
d
ELEVATION IN METERS
1000
500
200
100
0
0 50 km
USA
75°
74°
73°
72°
71°
70°

FIGURE 14: *Isochrone maps with contours in* 10^3 *years for (a-b) 3% and (c-d) 6%* Quercus *(oak) pollen.*

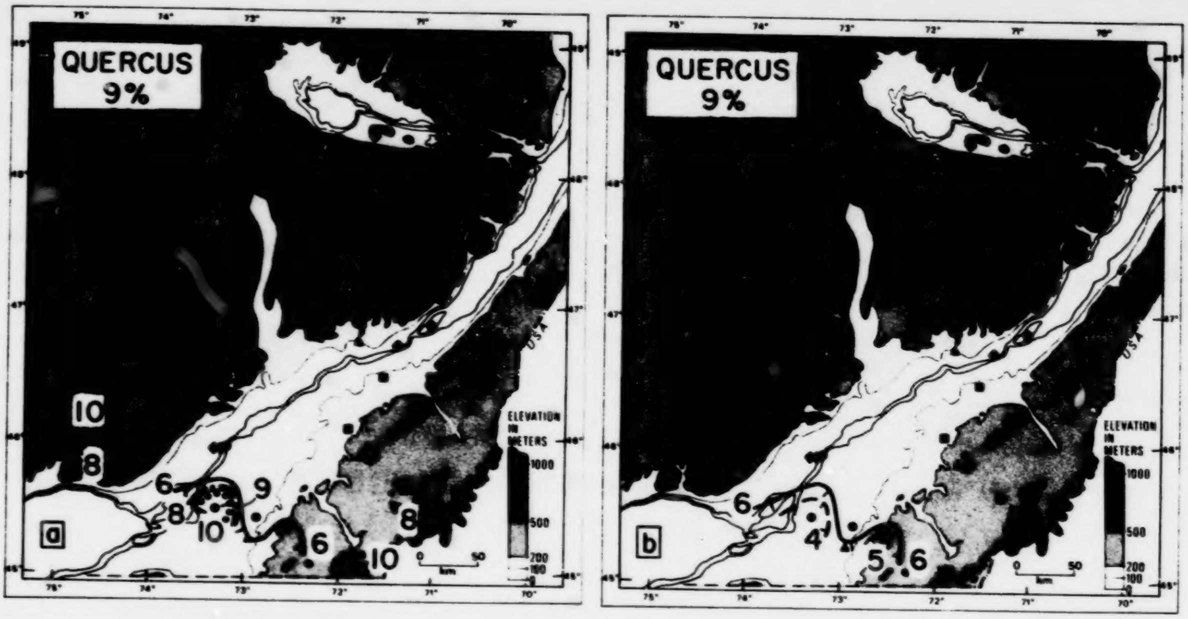

QUERCUS 9%
10
8
6
8
10
9
6
8
10
a
QUERCUS 9%
6
1
4
5
6
b
ELEVATION IN METERS
1000
500
200
100
0
0 50 km
U.S.A.
75°
74°
73°
72°
71°
70°

FIGURE 15: *Isochrone maps with contours in* 10^3 *years for (a-b) 9%* Quercus *(oak) pollen.*

trees also grew at moderate to high elevations just south of Lake Lampsilis in the east; but, to the south, southwest, and in the valley, *Pinus strobus* trees were prominent members of the forests. *Acer* populations were appreciable near two isolated sites in the south, and *Quercus, Ulmus,* and *Fraxinus* trees also grew in the southern forests. The southwest-to-northeast vegetational gradient from forests rich in *Pinus strobus* trees to open woodland and shrub-dominated vegetation included only a narrow band where populations of *Betula* shrubs and *B. papyrifera* trees were prominent.

By 6,000 yr B.P., forests occupied all but the highest elevations in the Laurentides, and *Tsuga, Acer,* and *Fagus* trees were well established in the southwest (Figures 17, 18). In contrast to 8,000 yr B.P., populations of *Betula* trees were widespread and numerous, and the forests with the highest abundances of *Pinus* trees were confined to a wedge bounded by the Laurentides in the northeast and by *Tsuga*- and *Betula*-rich forests in the south and southwest. The reemergence of *Betula* populations probably resulted from the spread of *Betula lutea,* particularly at moderate elevations in the south. A southwest to northeast gradient in forest composition had developed with a mixture of *Tsuga, Acer, Fagus,* and *Betula* trees in the southwest, abundant populations of *Pinus strobus* trees in the central region, and a mixture of *Picea, Abies,* and *Betula* trees at moderate to high elevations in the northeast.

With certain modifications, this pattern continued until after 4,000 yr B.P. (Figure 18). By this date, forests grew at almost all elevations in the northeast, and *Tsuga* populations were drastically decreased in the south. *Fagus* and *Acer* populations had expanded northeastward in the valley, and *Betula* populations had increased to the north and south of the valley. The wedge of prominent *P. strobus* populations remained in the central region, but the numbers of *Pinus* trees were lower than at 6,000 yr B.P.

By 2,000 yr B.P., *Tsuga* populations were again prominent in the southern forests, the area with high *P. strobus* populations had decreased to a minimum for the Holocene, and *Picea* and *Abies* populations had increased in the northeast and in the highlands south of the St. Lawrence River (Figure 19). A minimum in the modest *Quercus* populations also occurred. Mixed forests of *Tsuga, Fagus, Acer,* and *Betula* now graded into conifer forests to the north without a belt of *Pinus*-rich forests in between.

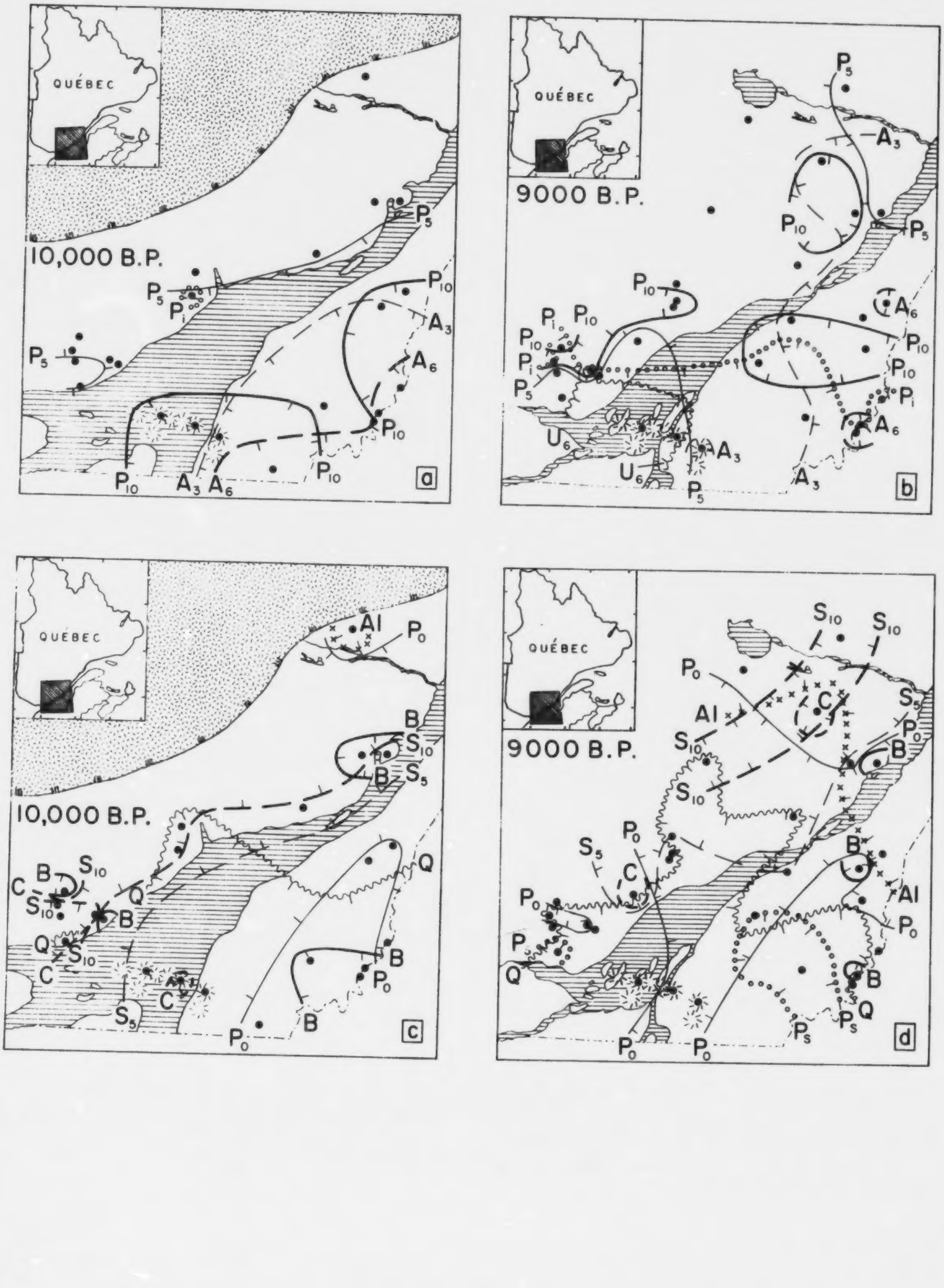
The increase in *Picea* and *Abies* populations continued through 500 yr B.P., *Quercus* populations increased in the southwest, and *P. strobus* populations increased modestly in the central area near the Mauricie River (Figure 19). At the same time, *Fagus, Acer, Tsuga, Betula, Ulmus,* and *Fraxinus* populations decreased moderately within the valley and to the south of it. These changes resulted in a vegetational gradient from mixed forests in the south and southwest to conifer forests in the north and east, particularly at high elevations. *Betula* trees were least abundant in the forests of the St. Lawrence River Valley and in the lowlands to the north.

At 500 yr B.P., the percentages of *Picea* and *Abies* pollen in the southeast were similar to those observed during the early Holocene (Figures 16, 19). The vegetation in the rest of southern Québec, however, differed greatly from any early Holocene pattern. Closed forests grew in the entire area, and mixed forests with *Tsuga, Acer, Betula,* and *Fagus* trees prevailed in the southwest. The treeless vegetation of the early Holocene had disappeared along with the extensive forests having large populations of *Pinus* trees. These vegetational differences probably reflect how much the early Holocene climates within southern Québec differed from late-Holocene climates both in seasonality and in the climatic gradients. Climatic calibration studies are now in progress to gain maps of these gradients, and these maps will be added to those from the Midwest (Bartlein and Webb 1982).

DISCUSSION

The maps portray many of the major trends and events within the Holocene vegetational history of southern Québec, even though only a small portion of the available pollen data was presented. The data shown were carefully selected to allow interpretations about past vegetational patterns and changes. The temporal and spatial contrasts in southern Québec are large enough that they can be monitored by pollen data without a need for exact corrections for the acknowledged biases within the pollen percentages (Davis 1963; Webb *et al.* 1978A). Approximate corrections were obtained by choosing low-valued isopolls for poorly represented types (e.g., *Abies, Acer*) and large-valued isopolls for well represented types (e.g., *Pinus* and *Betula*). The study of Webb *et al.* (1981), in which pollen and tree percentages were compared, guided these choices, but we

FIGURE 16: *Maps of selected isopolls for 10,000 (a,c) and 9,000 yr B.P. (b,d). The ticks along the isopolls point in the direction of increasing percentages for each pollen type. Indicators of conifer forest conditions are on (a-b) with 3%* (A_3) *6%* (A_6) Abies *and 5%* (P_5) *and 10%* (P_{10}) Picea *pollen. Also included are isopolls for 30%* Pinus *(Pi) and 6%* Ulmus-*plus*-Fraxinus (U_6) *pollen. The isopolls in (c-d) are from pollen types that mainly indicate treeless and open vegetation. These are 9%* Alnus crispa *(Al), 40%* Betula *(B), 10% Cyperaceae (C), 3%* Populus *(Po), and 5%* (S_5) *and 10%* (S_{10}) Salix-*plus* Artemisia-*plus-Gramineae pollen. Also indicated are isopolls for 20%* Pinus strobus *(Ps) and 6%* Quercus *(Q) pollen. The paleogeographic information on the location of the Laurentide ice sheet and the Champlain Sea at 10,000 yr B.P. are from Prest (1969) and Elson (1969). The base map for 8,000 yr B.P. was used to plot the data from 9,000 yr B.P. The ice sheet had retreated from the mapped region by then, but Lake Lampsilis occupied a slightly larger area at 9,000 yr B.P. than that mapped.*


QUÉBEC
10,000 B.P.
P5
Pi
P10
A3
A6
a
9000 B.P.
U6
Pi
P10
P5
A3
A6
b
10,000 B.P.
Al
P0
B
S10
S5
C
Q
b
c
9000 B.P.
S10
P0
Al
C
S5
B
Q
Ps
d

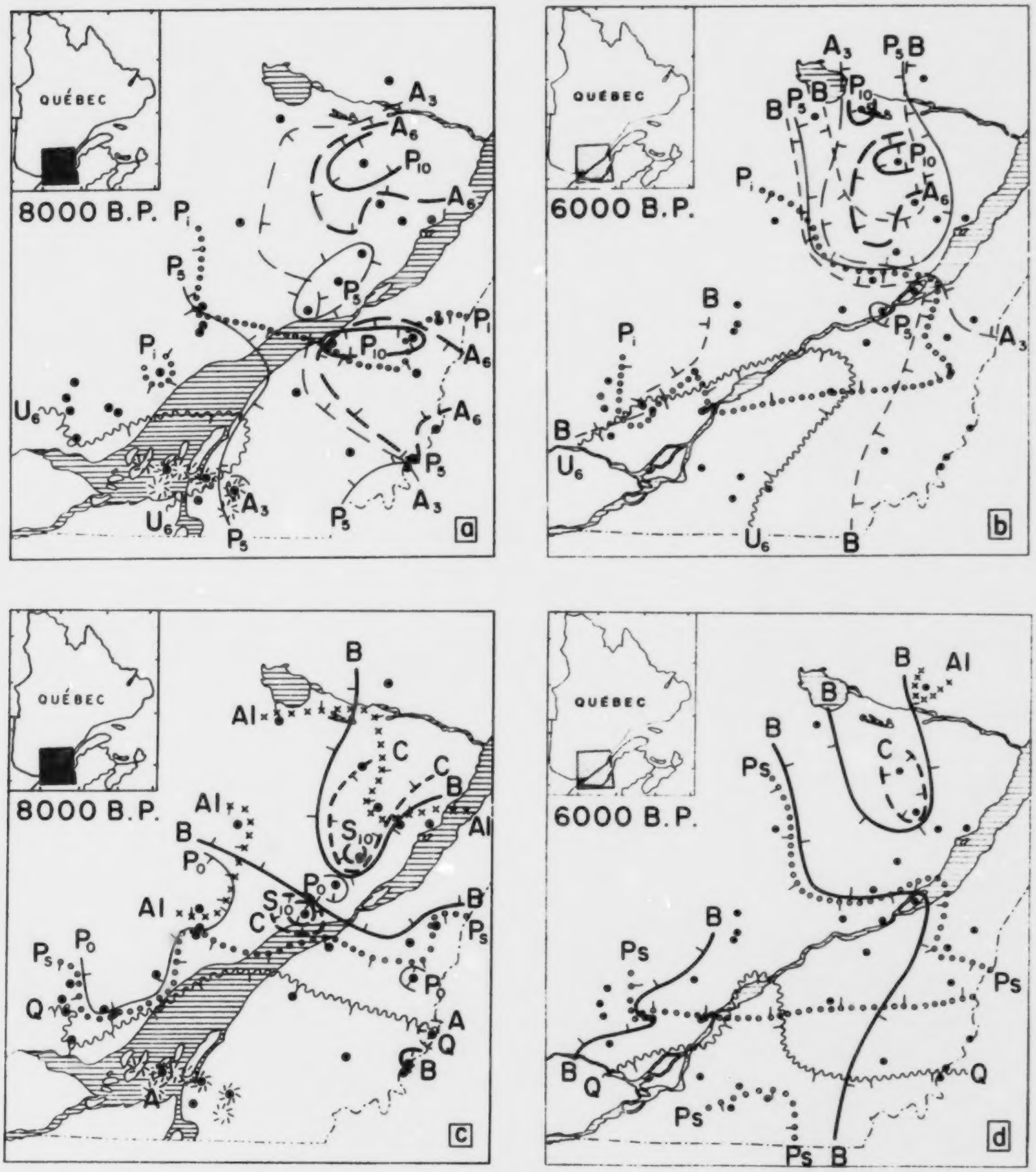

QUÉBEC
8000 B.P.
A3
A6
P10
P1
P5
U6
a
6000 B.P.
P5
B
b
Al
C
S10
P0
Ps
Q
A
c
d

FIGURE 17: *Maps of selected isopolls for 8,000 (a,c) and 6,000 yr B.P. (b,d). See* FIGURE 16 *for a key to the labels of the isopolls. The paleogeographic information for the position of Lake Lampsilis is from Brown-Macpherson (1967) and Elson (1969).*

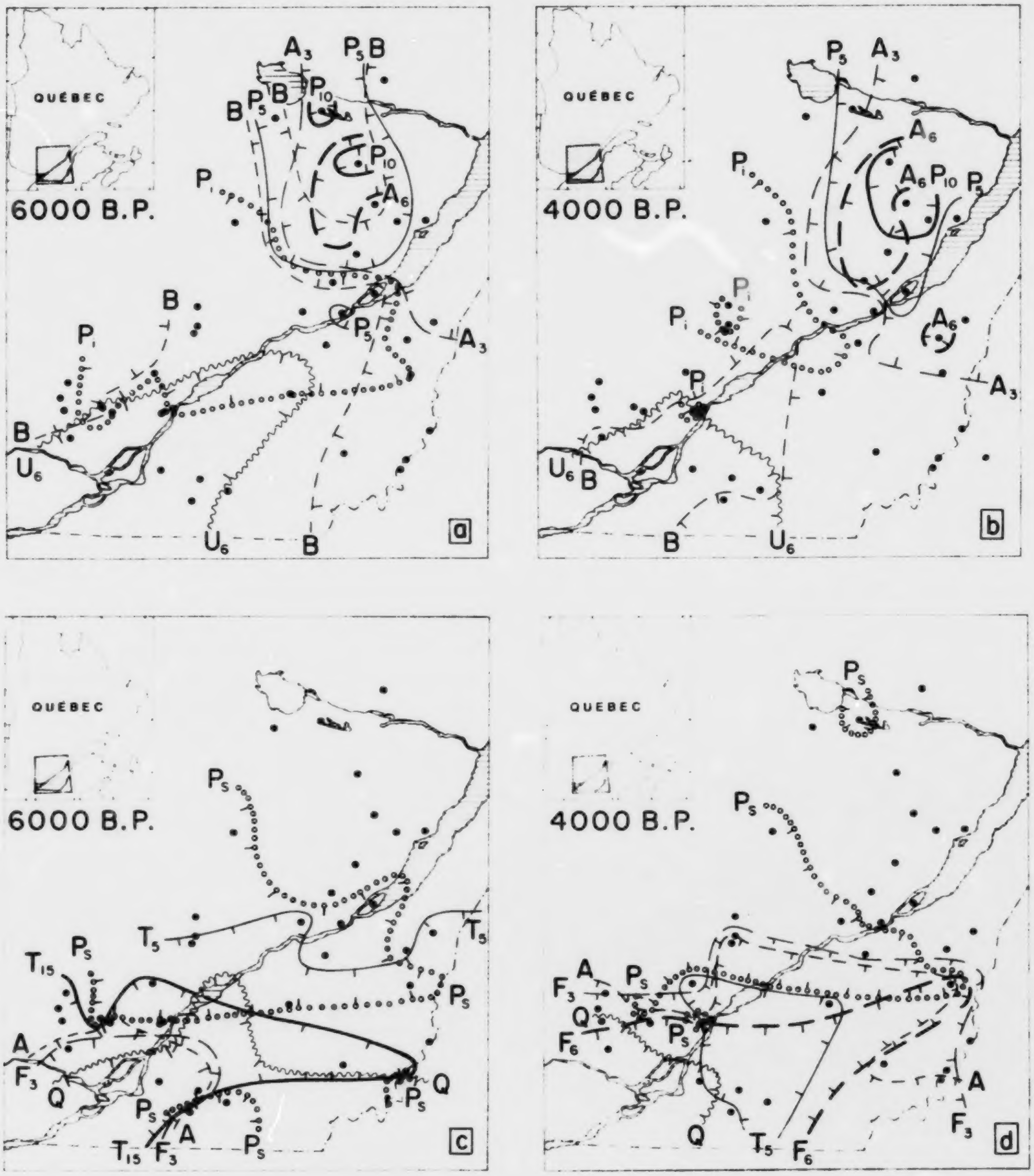

QUÉBEC
6000 B.P.
A3
P5 B
B P5 B
P10
P1
P10
A6
B
P1
P5
A3
B
U6
U6
B
a
QUÉBEC
4000 B.P.
P5 A3
A6
P1
A6 P10 P5
P1
P1
A6
P
A3
U6 B
B
U6
b
QUÉBEC
6000 B.P.
Ps
T5
T5
T15
Ps
Ps
A
F3
Q
Ps
Q
Ps
A
Ps
T15 F3
c
QUEBEC
4000 B.P.
Ps
Ps
A
F3
Ps
Q
Ps
F6
A
F3
Q
T5
F6
d

FIGURE 18: *Maps of selected isopolls for 6,000 (a,c) and 4,000 yr B.P. (b,d). See* FIGURE 16 *for a key to labels of the isopolls in (a-b). Indicators of mixed conifer-hardwood forests appear on (c-d) which have isopolls for 3%* Acer *(A), 3% (F_3) and 6% (F_6)* Fagus, *20%* Pinus strobus *(Ps), 6%* Quercus *(Q), and 5% (T_5) and 15% (T_{15})* Tsuga *pollen.*

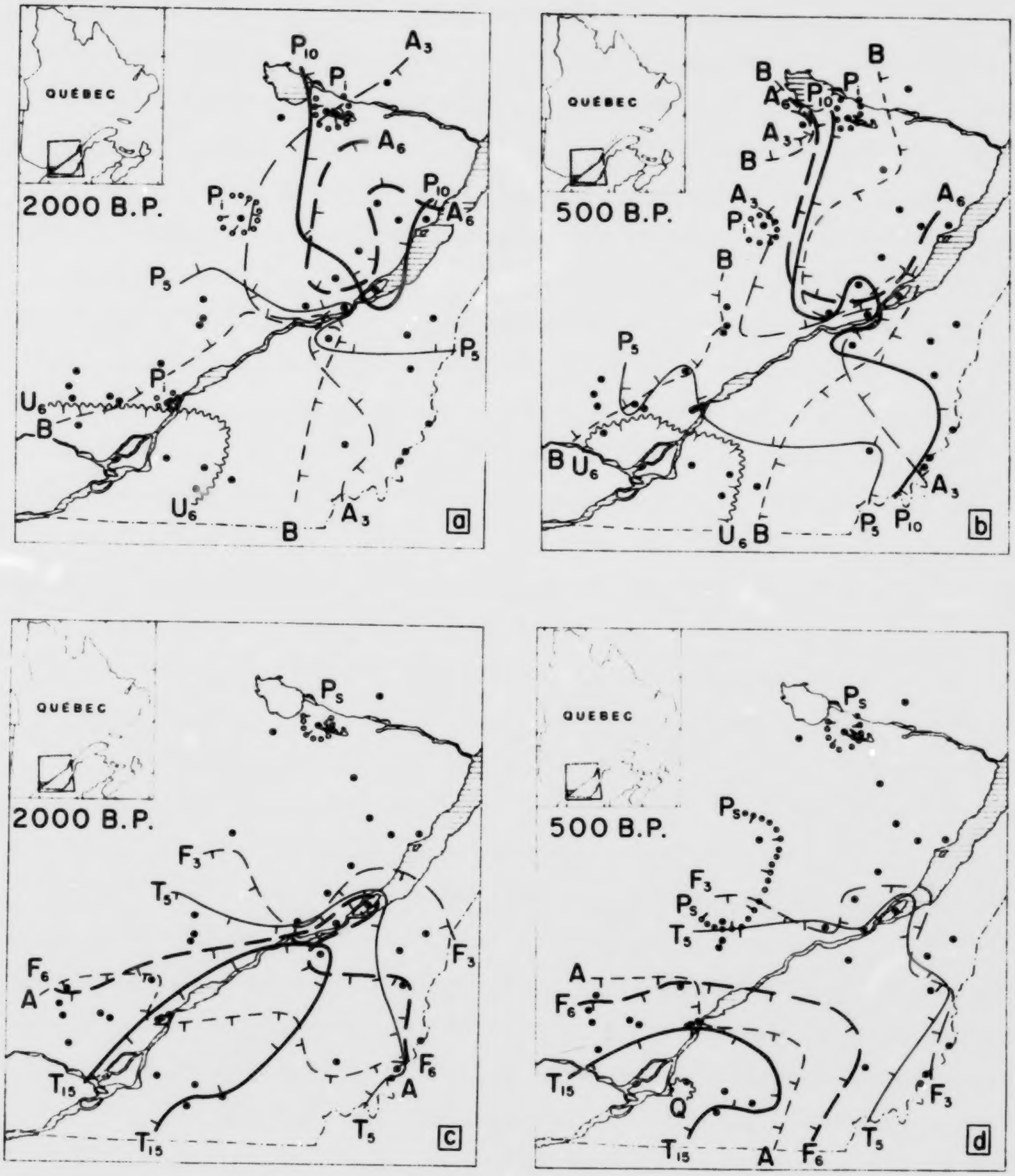

QUÉBEC
2000 B.P.
P_{10}
A_3
P_1
A_6
P_{10}
A_6
P_1
P_5
P_5
P_1
U_6
B
U_6
B
A_3
a
QUÉBEC
500 B.P.
B
B
A_6
P_{10}
P_1
A_3
B
A_3
P_1
A_6
B
P_5
B
U_6
A_3
U_6
B
P_5
P_{10}
b
QUÉBEC
2000 B.P.
P_5
F_3
T_5
F_6
A
F_3
T_{15}
F_6
A
T_{15}
T_5
c
QUEBEC
500 B.P.
P_5
P_5
F_3
P_5
T_5
A
F_6
T_{15}
Q
T_{15}
A
F_6
T_5
F_3
d

FIGURE 19: *Maps of selected isopolls for 2,000 (a,c) and 500 yr B.P. (b,d). See* FIGURES 16 *and* 18 *for a key to the labels of the isopolls.*

lacked such detailed guidance in choosing the isopolls for indicators of woodland and treeless vegetation. The main information about these vegetation types came from the isopoll maps of modern pollen data from northern Québec and Labrador (Davis and Webb 1975; Richard 1979; Elliot-Fisk *et al.* 1982).

Our level of vegetational interpretation of the mapped patterns seems well suited both to the data and to our models for interpreting the data. As we perfect the models developed by Andersen (1970), Parsons and Prentice (1980), Prentice (1982), and Webb *et al.* (1981) and obtain the data needed to calibrate these models, we may be able to estimate the past composition of the vegetation for certain areas at selected dates. For example, we may be able to list the complete composition of the forests near Montréal at 6,000 yr B.P. Such a description remains a challenge for palynology (Webb *et al.* 1981), but in attempting to meet this challenge paleocologists should not neglect the ability of uncalibrated pollen data, when properly displayed, to depict many key aspects of past vegetational dynamics (Webb *et al.*, in press).

Our maps from southern Québec add new information to the picture of vegetational change that was evident in the small-scale maps of Bernabo and Webb (1977). Comparing their maps with ours provides a "zoom-lens" view of eastern North American vegetational dynamics. Many of the same vegetational changes are evident on both the large-and small-scale maps, but the southern Québec maps illustrate details not seen at the subcontinent level. Certain of these details aid the climatic interpretation of the pollen data. For example, the southern Québec maps show patterns in the vegetation that reflect elevational contrasts of 200 to 500 m. This fine-scale vegetational sensitivity to environmental differences should help in resolving the degree to which the vegetation was in equilibrium with climate. The behaviour of pollen types and plant populations along elevational gradients can be compared to their behaviour along latitudinal gradients, and can be used to test whether climatic factors might be influencing the abundances and range of certain taxa. Davis *et al.* (1980) have recently used data from an elevational gradient in northern New England to document certain climatic changes there. Their interpretation of climatic conditions warmer than today from 9,000 to 2,000 yr B.P. is consistent with the trends in southern Québec. In another study, Gaudreau (1982) has assembled pollen data from several sites in order to describe the vegetational contrasts between the Hudson River Valley and the uplands to the east.

The "zoom-lens" approach to vegetational history requires further development. For example, magnification could be added to the "lens" in southern Québec, if a network of pollen data from small hollows and mor-humus profiles were assembled (Andersen 1978; Jacobson and Bradshaw 1981; Heide and Bradshaw 1982). Such a network would reveal variations within the vegetation that are not evident in our study. Regional versus local variations could be resolved. Such an addition should be a major goal in paleoecological research.

The maps for southern Québec show that most late-Holocene changes in the vegetation differ from the early Holocene changes both in direction and in character. At 10,000 yr B.P., treeless and open vegetation grew in the north. It decreased in area until 6,000 yr B.P. and finally disappeared before 5,000 yr B.P. in the Laurentide Highlands. Populations of *Picea, Abies, Ulmus,* and *Fraxinus* all increased in abundance northward until 6,000 yr B.P. and then shifted southward after 4,000 yr B.P. *Pinus* trees entered from the south after 10,000 yr B.P., and were widespread and abundant at 8,000 yr B.P. But from then to 2,000 yr B.P., their main populations decreased strikingly in size and area and shifted to the west and north. Like the *Pinus* populations, *Quercus* trees were more abundant in the early Holocene than later. Because *Quercus* trees were at the northern edge of their range in southern Québec, they never reached more than moderate abundances near a few sites.

After 8,000 yr B.P., *Betula* trees (mostly *B. lutea*) replaced the *Pinus* trees at moderate elevations in the south, and *Tsuga, Fagus,* and *Acer* trees replaced the *Pinus* populations in the St. Lawrence River Valley. *Betula* populations also increased within the Laurentides, and by 4,000 yr B.P. all but two sites in southern Québec had more than 40% *Betula* pollen. Although a mixture of northern hardwood and *Tsuga* trees dominated in the valley to the southwest from 6,000 yr B.P. onwards, the composition of the forests changed continuously. For example, the populations of *Tsuga* increased steadily from 7,500 to 5,000 yr B.P., declined abruptly about 4,700 yr B.P. (Davis 1981B; Webb 1982) and then reemerged after 3,000 yr B.P. During this time, *Fagus* extended its range northeastwards until 2,000 yr B.P.

The net effect of this sequence of changes is an asymmetry in the vegetational history during the Holocene. The late-Holocene changes differ from those during the early Holocene.

Why such a pattern occurred is yet to be fully explained. One set of factors influencing the differences in vegetation are those identified by Iversen (1958) in his descriptive model for vegetational change during a glacial/interglacial cycle. These factors include the leaching and acidification of upland soils and the differential migration of certain trees. Another factor not emphasized by Iversen (1958) is the climatic differences between the early and late-Holocene. These differences in moisture, temperature, seasonality, and circulation could easily account for most of the asymmetry in the Holocene vegetational history. The early Holocene may have been drier than the late Holocene, and the seasonal contrast in the early Holocene may have been greater than the contrast today (Kutzbach 1981; Kutzbach and Otto-Bliesner 1982). How large a role these climatic contrasts played is still to be determined. Further research is required that will show what combination of climatic, edaphic, and biological factors can explain the observed vegetational changes.

This interpretative work will be helped when the maps from southern Québec can be tied into maps of recently available data from Ontario (McAndrews 1981), Manitoba (Ritchie 1976), central Québec (Richard 1979, 1980; Richard *et al.* 1982), and the Arctic (Nichols 1975; Short and Nichols 1977; Andrews and Diaz 1981; Richard 1981A). Our study is a first step toward this larger research goal, and the computer programs used in our study should aid this research

SUMMARY

Sixty-six maps display the information from a network of 43 radiocarbon-dated pollen diagrams and illustrate the sequence of Holocene vegetational change in southern Québec. Isochrone maps show the temporal trends in selected isopolls (isofrequency contours) for 13 arboreal pollen types (*Abies, Acer, Betula, Fagus, Fraxinus, Juniperus/Thuja, Picea, Pinus, P. strobus, Populus, Quercus, Tsuga,* and *Ulmus*), 3 shrub types (*Alnus, A. crispa,* and *Salix*), and 3 herb types (*Artemisia,* Cyperaceae, and Gramineae). Plant populations are shown to change continuously in location, range, and abundance from 10,000 to 500 yr B.P. A series of composite maps were also plotted for certain dates with each map displaying selected isopolls from several pollen types. These maps illustrate the patterns in the vegetation at each date and also show the interactions among plant populations as the vegetational patterns changed.

The isochrone and composite maps show that from 10,000 to 6,000 yr B.P., first *Populus* (aspen) woodlands and then forests of *Picea* (spruce), *Abies* (fir), and *Betula* (birch) trees replaced the treeless or very open vegetation that grew north of the Champlain Sea at 10,000 yr B.P. These forests grew only in the Eastern Townships and Beauce in the southeast corner of Québec at 10,000 yr B.P., moved northward until 6,000 yr B.P., and then extended their southern border southward after 4,000 yr B.P. Forests rich in *Pinus* (pine) trees entered from the southwest at 9,000 yr B.P., were widespread and dominated by *Pinus strobus* (white pine) by 8,000 yr B.P., and then were largely replaced by mixed forests of *Tsuga* (hemlock), *Fagus* (beech), *Acer saccharum* (sugar maple), and *Betula* (probably *B. lutea* -- yellow birch). Within these mixed forests, the composition changed continuously as *Tsuga* trees appeared about 7,000 yr B.P., became widespread and abundant in the south by 5,000 yr B.P., declined abruptly in abundance about 4,700 yr B.P., and then reemerged in abundant quantities after 3,000 yr B.P. Populations of *Fagus* trees arrived at about 6,000 yr B.P. and extended their range northward to Québec City until 2,000 yr B.P. The populations of *Tsuga, Fagus, Acer, Betula, Ulmus* (elm), and *Fraxinus* (ash), decreased moderately in abundance from 2,000 to 500 yr B.P. as populations of *Picea, Abies,* and *Alnus* (alder) increased in the north and southeast.

SOMMAIRE

L'histoire holocène de la végétation du Québec méridional est illustrée par 66 cartes des paléo-isopolles provenant d'un réseau de 43 diagrammes polliniques datés au radiocarbone. Des cartes isochrones permettent de décrire les gradients spatio-temporels de certains isopolles (lignes de même fréquence) pour 13 types polliniques arboréens *(Abies, Acer, Betula, Fagus, Fraxinus, Juniperus/Thuja, Picea, Pinus, P. strobus, Populus, Quercus, Tsuga* et *Ulmus)*, 3 types arbustifs *(Alnus, A. crispa* et *Salix)* et 3 types herbacés *(Artemisia,* Cyperaceae et Gramineae). Les populations végétales montrent des changements ininterrompus entre 10,000 et 500 ans avant l'actuel, tant dans leur localisation que dans leur extension géographique et dans leur abondance. Une autre série de cartes a été produite illustrant, pour une époque donnée, certains isopolles de taxons choisis. Ces cartes montrent l'intéraction des populations végétales à chaque époque, et les changements d'une époque à l'autre.

Les cartes d'isochrones et d'interaction montrent qu'entre 10,000 et 6,000 ans B.P., au nord de la mer de Champlain puis du lac à Lampsilis, le paysage initial dépourvu d'arbres a été envahi d'abord par une forêt-parc à *Populus*, puis par des forêts d'épinettes *(Picea)*, de sapins *(Abies)* et de bouleaux *(Betula)*. Ces forêts étaient confinées à l'Estrie et à la Beauce vers 10,000 ans B.P.; elles se sont ensuite déplacées vers le nord jusque vers 6,000 ans B.P. puis, après 4,000 ans B.P., leur marge méridionale s'est étendue vers le sud. Des forêts riches en pins *(Pinus)* ont migré dans la région par le sud-ouest vers 9,000 ans B.P.; elles étaient largement distribuées vers 8,000 ans B.P., dominées par le pin blanc *(Pinus strobus)*; elles furent par la suite remplacées largement par des forêts mixtes de pruche *(Tsuga)*, hêtre *(Fagus)*, érable à sucre *(Acer saccharum)* et bouleau *(Betula* cf. *lutea)*. Ces forêts ont connu d'incessants changements dans l'abondance relative des espèces. La pruche *(Tsuga)*, apparue vers 7,000 ans B.P., s'est multipliée et largement dispersée jusque vers 5,000 ans B.P.; son abondance a brusquement chuté vers 4,700 ans B.P. après quoi, surtout après 3,000 ans B.P., elle est redevenue un élément important du couvert forestier. Le hêtre *(Fagus)* est arrivé vers 6,000 ans B.P. et s'est étendu vers Québec jusque vers 2,000 ans B.P. De 2,000 à 500 ans avant l'actuel, les populations de *Tsuga, Fagus, Acer, Betula, Ulmus* (orme) et *Fraxinus* (frêne) ont légèrement diminué d'importance au profit des populations de *Picea, Abies* et *Alnus* dont l'abondance s'est accrue de part et d'autre de la vallée du Saint-Laurent.

ACKNOWLEDGMENTS

Grants to COHMAP (Cooperative Holocene Mapping Project) by the National Science Foundation Program for Climate Dynamics (ATM79-16234 and ATM81-11870), and a contract from the United States Department of Energy Carbon Dioxide Research Division supported this research. M. Anderson, R. Arigo, J. Avizinis, L. Briendel, C. Collins, D.C. Gaudreau, R.M. Mellor, and S. Suter provided technical assistance, and we thank J.T. Overpeck for critically reading a final draft of this manuscript.

The Natural Sciences and Engineering Research Council of Canada and the Fonds F.C.A.C. of the province of Québec provided grants for pollen analyses through Pierre Richard and the Laboratoire de paléobiogéographie et de palynologie, Université de Montréal. The help of

Helene Jette, Pierre Pare, Nicole Morasse, Alayn Larouche and many graduate students is warmly acknowledged. Mrs. L.D. Farley-Gill of the Quarternary Paleoecology Laboratory of the Geological Survey of Canada aided in compiling the pollen data.

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APPENDIX 1

For comparison with the maps of Holocene data, we produced isopoll maps from 79 sites with contemporary pollen data (Figures 19-23). These maps update those of Webb *et al.* (1978B) and use the same base maps and contour intervals as those applied to the Holocene data. Only 60 sites appear on the maps because the close spacing of certain sites required mapping average values of two or more sites at 17 locations.

The 79 sites were chosen from the 84 sites available in the mapped region of southern Québec. The five sites that were deleted contained no counts for herbaceous pollen types and were located near sites with records for all pollen types. Twelve other sites contained no records of herbaceous pollen, but their data were included to enlarge the network of sites used for drawing contours (Figure 20). The data set also included five sites in which Compositae pollen was recorded but not split into *Ambrosia* or *Artemisia* pollen. The mapped data came from core tops at 28 Holocene sites (Table 1) and from modern or core-top samples collected at 34 sites by Richard (1976), seven sites by Potzger (1953), one site by Potzger and Courtemanche (1954), three sites by Potzger and Courtemanche (1956), one site by Potzger *et al.* (1956), two sites by Cain and Cain (1954), two sites by Terasmae (1960), and one site by LaSalle (1966).

In the last 400 years, human disturbance has increased the values of the herbaceous pollen at many sites (Van Zant *et al.* 1979). We therefore used a sum of tree and shrub pollen (minus Ericaceae pollen) to calculate the percentages for arboreal types. For Ericaceae and herbaceous pollen types, we used a sum of total pollen minus spores and aquatic pollen types.

The patterns for several pollen types illustrate how the boreal forest, which grows in the north and in the highlands of the southeast (Figure 2), differs in composition from the mixed forest. The values of *Picea, Abies, Alnus* pollen and *Pinus banksiana/resinosa* (diploxylon grains) (Figures 20, 21A, 22D) are highest at sites located in the boreal forest, whereas the values of *Tsuga, Fagus, Acer, Ulmus*-plus-*Fraxinus,* and *Quercus* pollen are highest in the southwest (Figures 21D; 23 B-D). These patterns are evident even though *Betula* and *Pinus* pollen dominate over most of the study area and combine to account for 45 to 75% of the pollen at each site (Figures 22A,B). *Betula* is the most abundant pollen type and is only less than 20% at two sites outside of the northern Laurentides. The percentages of *Pinus* pollen are highest in the north and west where *P. strobus* is the main contributor (Figure 22C). The highest values of *Juniperus/Thuja* pollen are in the Laurentides north of Montréal (Figure 23A).

In contrast to the maps for 500 yr B.P. (Figure 19), the values of herbaceous pollen are high in the south (Figure 24). *Ambrosia* and Gramineae are the two main types whose values were increased by human disturbance of the forests. The high values of Cyperaceae and Ericaceae pollen, however, reflect the local growth of these plants near the pollen samples. Fifty-eight of the 79 samples came from bogs or moss polsters, and therefore may be from habitats where sedge and ericaceous plants can grow.

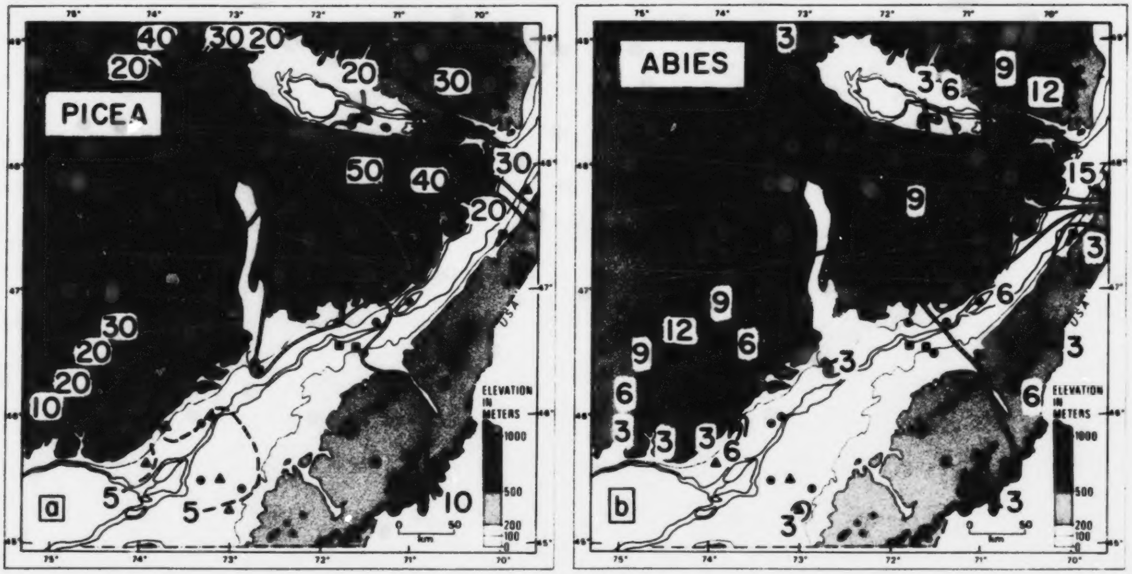
PICEA
ABIES
a
b
40
30
20
20
20
30
50
40
30
20
30
20
20
10
5
5
10
3
3
6
9
12
15
9
3
6
9
12
9
6
6
3
3
3
3
6
3
6
3
3
ELEVATION IN METERS
1000
500
200
100
0
0
50
km
U.S.A.
75°
74°
73°
72°
71°
70°
47°
45°

FIGURE 20: *Iscpoll maps for modern percentages of (a)* Picea, *and (b)* Abies *pollen. The circles locate sites whose data came from the tops of Holocene cores, the squares and triangles locate sites whose data came from surface sediments, peats, or moss polsters; but the data from triangle sites contain no separate counts either for* Ambrosia *pollen or for any herbaceous pollen types including* Ambrosia *pollen.*

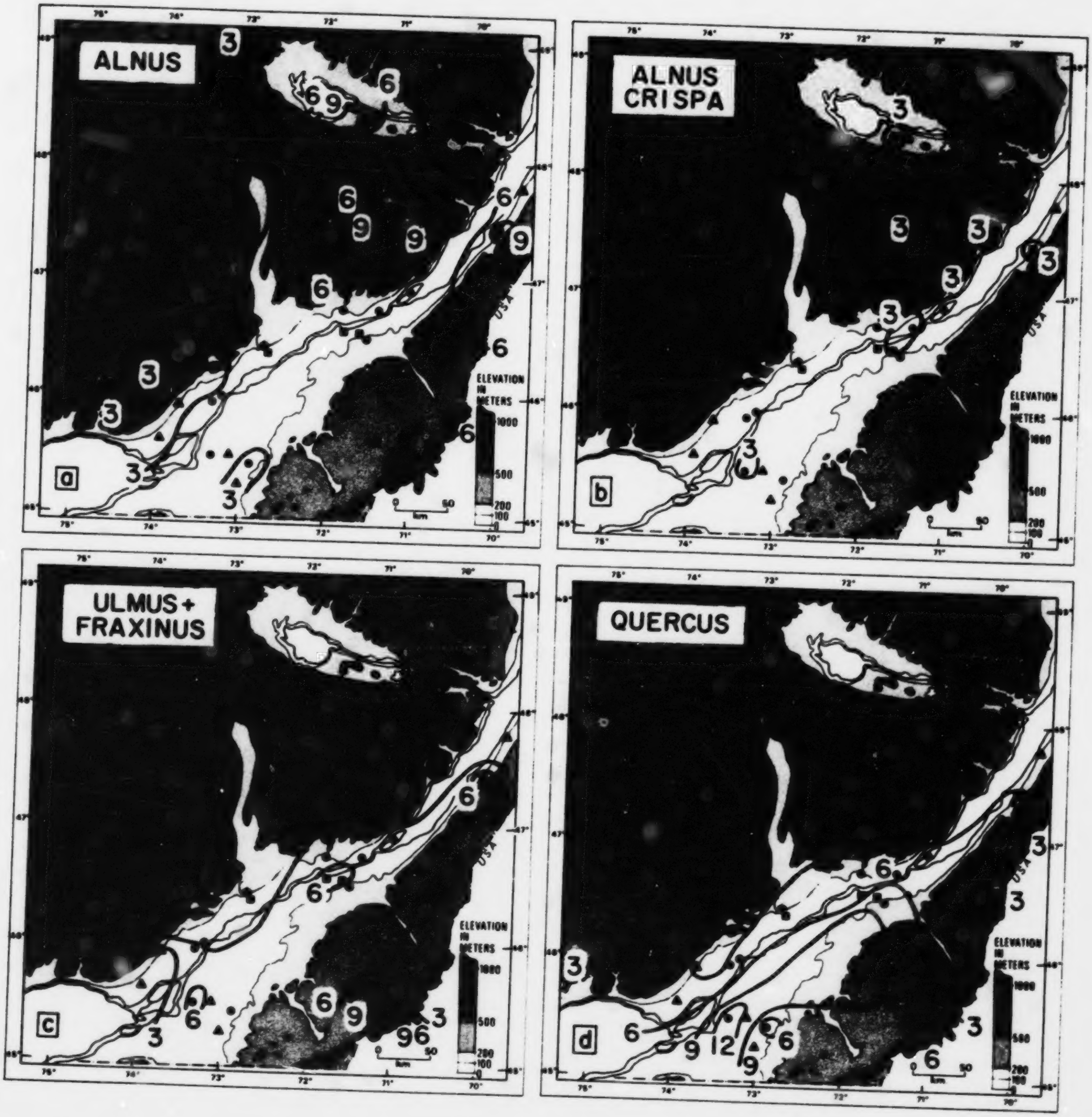
ALNUS
ALNUS CRISPA
ULMUS + FRAXINUS
QUERCUS
a
b
c
d
USA
ELEVATION IN METERS
1000
500
200
100
0
0 km 50
75°
74°
73°
72°
71°
70°
48°
47°
46°
45°

FIGURE 21: *Isopoll maps for modern percentages of (a)* Alnus, *(b)* Alnus crispa, *(c)* Ulmus-*plus*-Fraxinus, *and (d)* Quercus *pollen.*

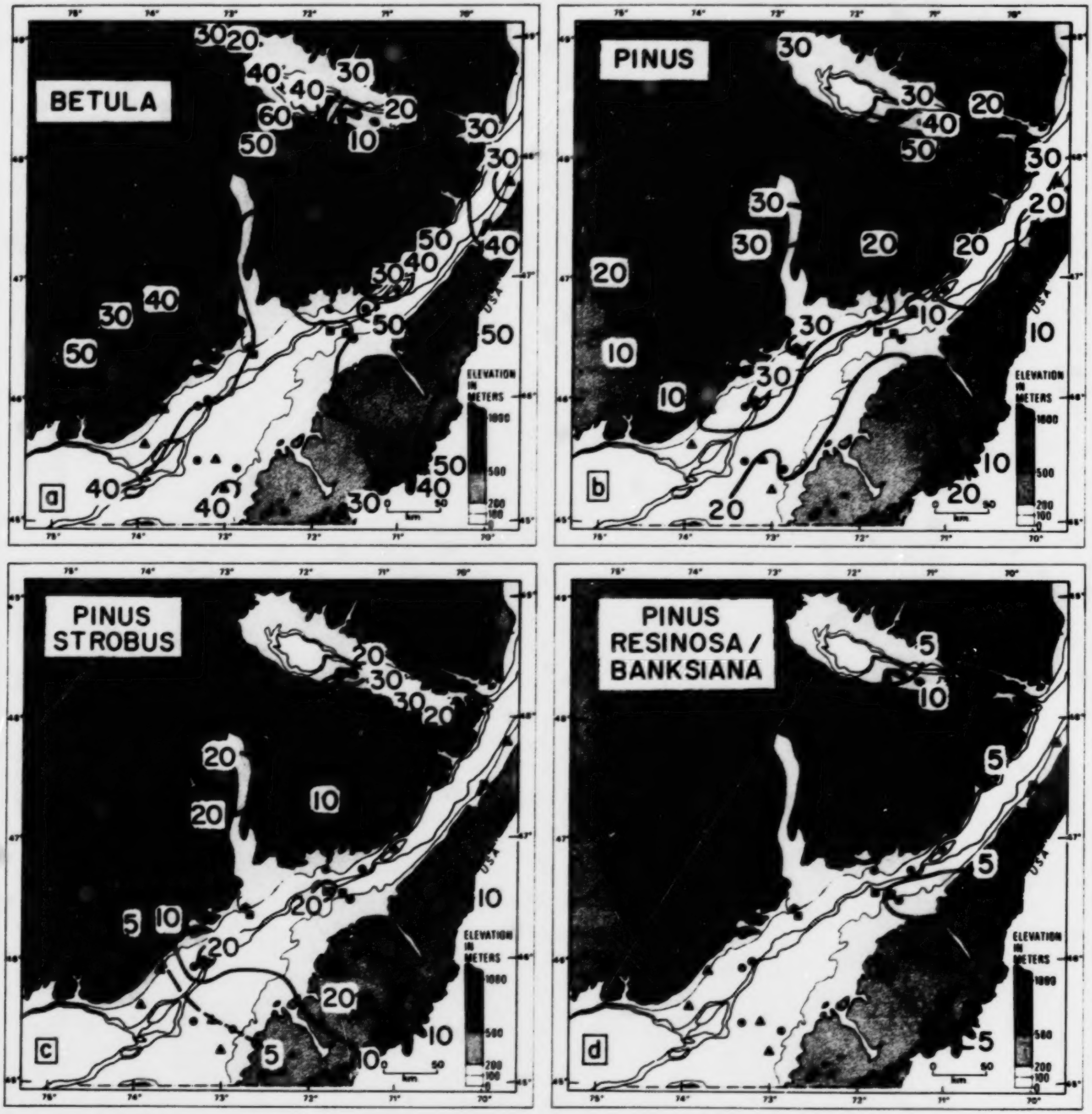
BETULA
PINUS
PINUS STROBUS
PINUS RESINOSA / BANKSIANA
a
b
c
d
ELEVATION IN METERS
1000
500
200
100
0
km
0
50
USA
75°
74°
73°
72°
71°
70°

FIGURE 22: *Isopoll maps for modern percentages of (a)* Betula, *(b)* Pinus, *(c)* Pinus strobus *(haploxylon grains), and (d)* Pinus banksiana/resinosa *(diploxylon grains) pollen.*

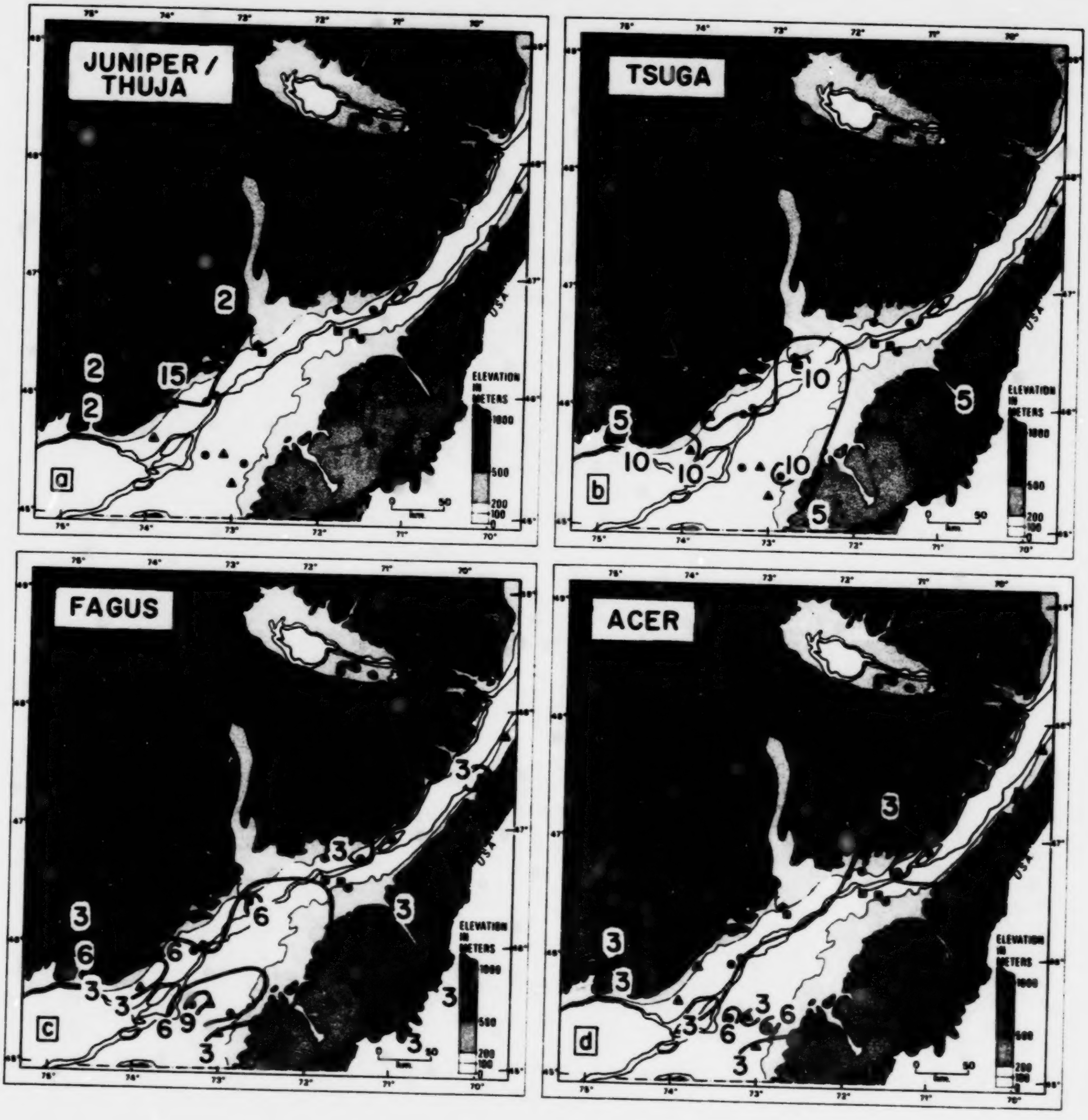
JUNIPER/ THUJA
TSUGA
FAGUS
ACER
a
b
c
d
ELEVATION IN METERS
1000
500
200
100
0
km
USA
75°
74°
73°
72°
71°
70°

FIGURE 23: *Isopoll maps for modern percentages of (a)* Juniperus/Thuja, *(b)* Tsuga, *(c)* Fagus, *and (d)* Acer *pollen.*

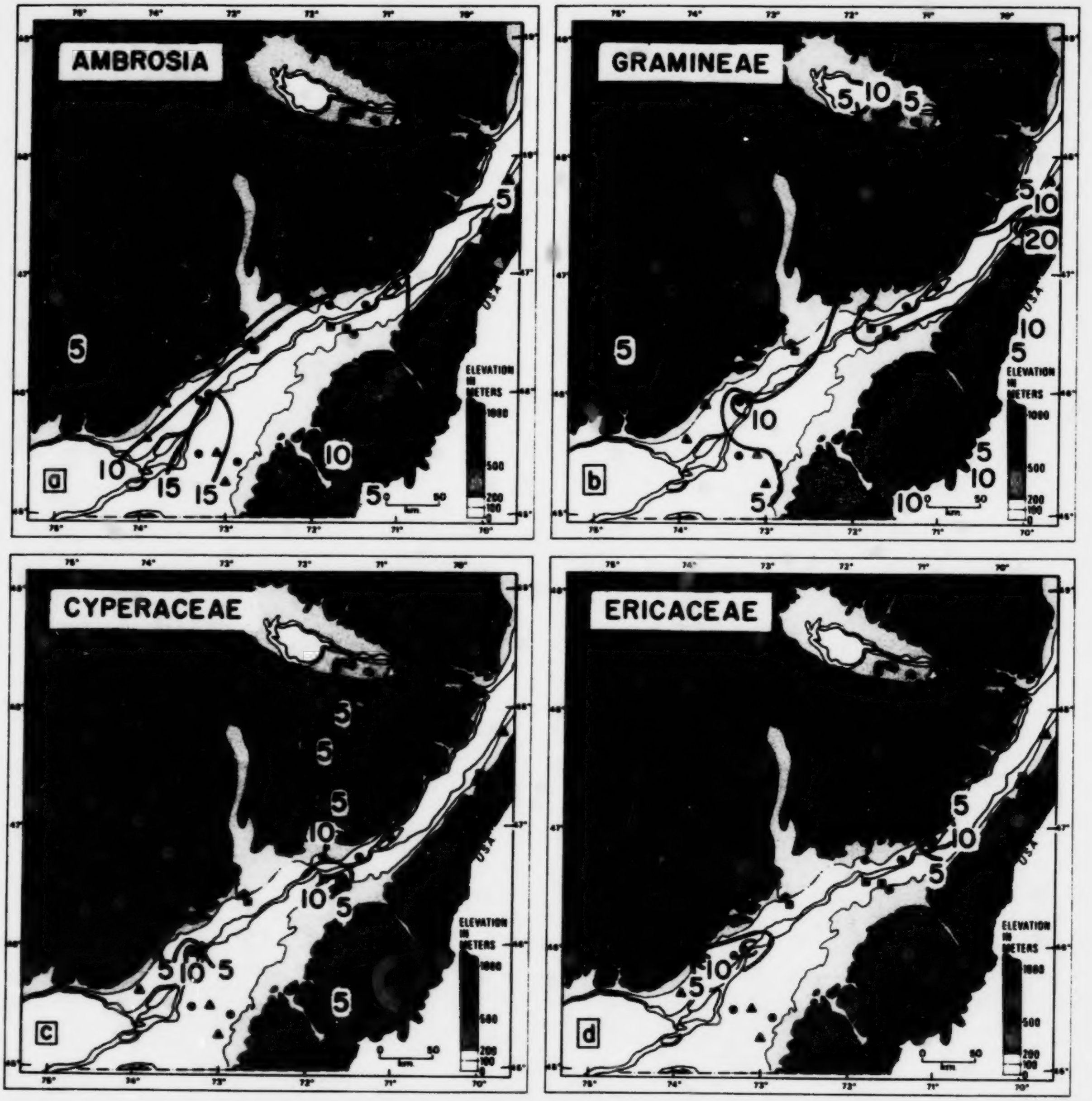
AMBROSIA
GRAMINEAE
CYPERACEAE
ERICACEAE
a
b
c
d
ELEVATION IN METERS
1000
500
200
100
0
0 50 km
USA
75°
74°
73°
72°
71°
70°
5
10
15
20

FIGURE 24: *Isopoll maps for modern percentages of (a)* Ambrosia, *(b) Gramineae, (c) Cyperaceae, and (d) Ericaceae pollen.*

RICHMOND LONGLEY AND CLIMATIC VARIABILITY IN CANADA

John M. Powell[1]

Richmond (Dick) W. Longley showed his interest in climate change and climate variability on a number of scales over a period of 40 years. One of his first published papers (Longley 1942) looked at the frequency distribution through the year of abnormally high and low daily mean temperatures at Toronto comparing them with a similar study at Greenwich, England, whereas one of his most recent contributions (Longley 1979) was an analysis of minimum temperatures in the Canadian Arctic.

Following his 1942 paper based on Toronto temperatures, he examined standard deviations of the mean daily temperature at 18 stations throughout Canada (Longley 1947). All stations had 50 or more years of record except Sable Island, Churchill, York Factory and Dawson. In this study, Longley calculated standard deviations for 48 days in the year on the 5th, 13th, 20th and 28th of each month, and showed, as expected, that winter temperatures were more variable than summer, and that maritime stations were less variable than continental stations. Changes from winter to summer, and vice versa, were shown to occur abruptly rather than gradually. Later he published (Longley 1951A) on the daily variation of temperature at 19 stations across Canada, and on differences of the temperature extremes at stations in the Montréal Forecast Region (Longley 1951B).

The first thorough study of temperature trends in Canada[2] was conducted by Longley (1954B): it dealt with temperature cycles in 14 geographical districts of Canada based on data from 61 stations. This was a contribution to a climatic change panel discussion at the Toronto Meteorological Conference in September 1953. It is worth mentioning the results. In all districts in which records went back to 1880, the decade of the eighties was cold, with warming occurring thereafter. There was considerable variation between districts.

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[2] Ed. note: For a more recent study of temperature changes in Canada see Berry (1981).

The warmest decades were generally those ending in the 1930s, though in the east the warmth continued until the late 1940s. By the late 1940s western Canada was definitely cooler. An elaboration of this study (Longley 1954A) summarized mean annual and 10-year running mean temperatures for the 62 selected stations for their period of record and values for the districts in which they were grouped.

Longley's (1958) studies of temperature fluctuations at Resolute, Northwest Territories included 7-day running means for 8 years of data, which showed fluctuations in mean daily temperatures of about 16 days - an average in good agreement with a more recent, broader study of 10 Canadian stations by Strong and Khandekar (1975). More recently, Longley (1979) extended his earlier study at Resolute to analysis of minimum winter temperatures at 20 stations in the Canadian Arctic from 1941 to 1977. He found that, on the average, the lowest temperature advances from south of the Arctic Circle in late January to the northern part of Ellesmere Island in the first week of March.

In 1967, Longley published a stimulating paper on changes in the frost-free period in Alberta. In it he compared the mean frost-free period for 1951-1964 with the years prior to 1951 for 68 stations grouped by river basins. In southeastern Alberta the increase in the frost-free period for the latter period was small, but stations in the North Saskatchewan River Basin showed increases of one full month, and several other areas two to three weeks. As frosts are associated with minimum temperatures in spring and fall, he examined 10-year running mean trends for these seasons at selected stations for periods of 50 years or more. This interest in frost data had been kindled earlier by his involvement in a climatic summaries publication (Boughner *et al.* 1956), which included an introduction on the frost-free season in Canada.

Longley also published extensively on variability of precipitation. Two early studies in this area (Longley 1952, 1953B) showed that the coefficient of variation was the best and most stable measure of variability of precipitation. The first paper used 30 British Columbia stations and four stations from neighbouring Washington with records of at least 30 years to test the relationship between precipitation and variability, developing coefficients of variation for July, December and annual precipitation totals. The second involved a wider geographic sample using annual precipitation totals for 142 stations across Canada and 34 in the adjacent areas of the United States based on the period 1900-1950.

Generally, minimum variability increases as one moves poleward. Variability is greatest in the central Prairies and least in the Maritimes, whereas the pattern in the mountains and valleys of British Columbia is irregular. In addition, Longley (1953A) investigated the length of dry and wet spells using data from Dawson, Victoria, Winnipeg, Montréal and St. John. He found that after a wet day the probability of the following day being wet is constant no matter how long the wet period has persisted. The same is true following a dry day except there is a slight increase in the probability of dry weather with increasing length of the dry period.

Twenty years later he produced another series of papers on precipitation. In a study dealing with the Canadian prairies, Longley (1972B) returned to the question of the length of wet and dry spells in the summer months based on studies of 21 stations divided equally between the three provinces. He also looked at the relationship between precipitation and distance to determine the extent to which rain at one location implies rain at another, using 24 stations largely in Alberta for the analysis. Variation of precipitation through the years of record was also analysed based on 10-year running mean annual precipitation for five river basins. The method had been used in "The Climate of the Prairie Provinces" (Longley 1972A), but in this case he stressed the need for care in the selection of stations to represent average values for a river basin. In the case of the Assiniboine River Basin, he showed that the major cause for the changes in annual precipitation during the previous 50 years was variation in the summer months. A paper (Longley 1974) on spatial variation of precipitation over the prairies through the period of record demonstrated that trends in precipitation are not the same throughout the main agricultural area of the Prairie Provinces. This conclusion was supported by correlation coefficients between precipitation amounts at pairs of stations and the particular direction in which storms move across the prairies, which varies from month to month during the summer season. He showed that a significant correlation exists between the monthly precipitation of two stations on the prairies when the distance between them is less than 400 km, and that the correlation is greater when the stations are east and west of each other, than when they are north and south of each other. In two papers (Longley 1973, 1975) he discussed the effect of prairie valleys on precipitation, finding that precipitation in a valley is 10 to 20% below that on the surrounding plain.

In his publications on local climate, or in his textbooks, Longley usually included a section on climatic trends or change. For example, in "The Climate of Montreal" (Longley

1954C) he gives mean departure from normal for 10-year periods for mean annual temperature, annual rainfall, and seasonal snowfall from 1880 to 1950. The trends were found to be similar to those of western Europe for the same period, and he mentions the trends in Europe for the preceding 150 years.

The textbook "Elements of Meteorology" (Longley 1970) contains a whole chapter on climatic change, and it is here we note his interest in the entire subject as he discusses likely causes for change - the solar constant, albedo, long-wave radiation.

"The Climate of the Prairie Provinces" (Longley 1972A) includes part of a chapter on climatic change, with regional examples for temperature and precipitation. In this study, he shows mean annual temperature for the Prairies south of 55°N rose about 0.8°C from the late 1800s until about 1910. From 1920 to 1950, the mean stayed between 2.8 and 3.3°C - the warmest decade being 1925-1934. The years 1945-1960 were generally cold with a minimum of 2.2°C for the decade ending in 1956, since when the 10-year mean has risen as high as 3.0°C in 1961. The study of the oil sands area in Alberta (Longley and Janz 1978) includes discussions of annual temperature trends at Fort McMurray, and the use of this station to estimate areal temperature distributions.

A contract study (Longley 1977) examined climatic change as it affects Alberta and the other Prairie Provinces. This included comments on ancient and recent temperatures from various sources, before providing details of temperature and precipitation changes (especially for the growing season) on the prairies since records began in 1872 at Winnipeg. The study includes a section on trends in minimum temperatures and changes in the length of the mean frost-free period for a number of stations. Lacombe, for example, had a mean frost-free period of 62 days for 1908-1917, and of 98 days for 1941-1970.

In addition to these published contributions to our understanding of climate variability in Canada, Longley also sparked the interest of others in the subject. He taught meteorology to new recruits for the Canadian Meteorological Service in Toronto during World War II. Then, for over a decade beginning in 1959, he taught meteorology at the University of Alberta. During this period, many of his students wrote term papers on climatic variability, and some prepared theses on the topic under his guidance. Richmond Longley contributed significantly to our knowledge of Canadian climate, and he was a Canadian pioneer in the study of climate variability using the instrumental record. In reviewing the first volume of this series just before his death, Longley (1981) concluded with the sentence, "One can only wish the research staff of the National Museum every success with a project that promises to become the definitive work on climatic change in Canada."

The above discussion provides some highlights of Longley's many studies concerning climate variability. A biographical sketch listing all of his publications in meteorology up to 1977 is included in the special volume to honour him on the occasion of his 70th birthday (Hage and Reinelt 1978). In order to complete their list, I have included more recent publications in a separate section after the normal references.

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